IMPLICATIONS OF SEISMIC ACTIVITY AT THE CLARK HILL RESERVOIR

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CERTIFICATE OF THESIS APPROVAL

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IMPLICATIONS OF SEISMIC ACTIVITY AT THE CLARK HILL RESERVOIR

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Implications of Seismic Activity at the Clark Hill Reservoir

H. Edward Denman, Jr.

103 Pages

Directed by Dr. L. T. Long

On November 1, 1875 at 21:55 GMT east-central Georgia experienced an earthquake which produced a maximum Modified Mercalli Intensity of VI in the Washington-Lincolnton, Georgia area. This shock was felt over an area of 25,000 square miles and is reported to have lasted approximately thirty seconds in the epicentral area. The earthquake was felt from Atlanta, Georgia to Columbia, South Carolina and from Gainesville to Savannah, Georgia. This event ranks as one of the four significant earthquakes which have occurred within the state.

Examination of seismograph records from the ATL WWSS station revealed thirteen seismic events of local magnitude (M_L) between 2.5 and 3.6 which have occurred in the Clark Hill area over the past ten years. Relocation of these epicenters places the earthquakes in central and southern Lincoln County between the Savannah River and the Little River in Georgia. These locations indicate a localized zone of low level seismic activity at Clark Hill. The most recent event associated with this zone occurred on February 13, 1974 with local magnitude of 2.7 and epicenter located at 33.62^{o}N, 82.48^{o}W.

Local microearthquake surveys conducted between September, 1973 and April, 1974 recorded nine seismic events which could not be ascribed to local quarry activity and must therefore be considered as microearthquakes. Recording of a microearthquake on January 4, 1974 at 18:30 GMT with an epicenter at $33^{o}39.63'$, $82^{o}24.12'$ represents the first well located microearthquake detected in Georgia.

Bouguer anomalies computed from 311 gravity measurements reveal a breached, linear NE-SW trending ridge of anomalies in southern Lincoln County near Amity, Georgia which corresponds to the area of microearthquake locations. A right lateral strike slip displacement of approximately 2000 feet (0.6 km) is indicated by offset of these anomalies along a possible NW-SE striking fault. Velocity data from local quarry blasts indicate an average compressional wave velocity of 5.8 ± 0.5 km/sec for the Clark Hill area and a shear wave velocity of 3.4 ± 0.5 km/sec to a distance of 40 km.

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CHAPTER I

HISTORICAL INTRODUCTION

Georgia has experienced only four events of intensity V (Modified Mercalli) or greater for which epicenters are located within the state. These events occurred near Lincolnton, Savannah, Milledgeville, and Atlanta (Heck and Eppley, 1971). The earthquake at 21:55 GMT, on November 1, 1875 near Lincolnton, Georgia was one of the two largest in Georgia based on an epicentral intensity of VI. The epicenter of this event is placed on the basis of intensity data at latitude 33.8 degrees north and longitude 82.5 degrees west, within the central Savannah River basin of east-central Georgia. The felt area of the 1875 event covered 25,000 square miles, and shaking was reported in the cities of Atlanta, Gainesville, Macon, and Savannah in Georgia and in Columbia and Spartanburg, South Carolina (Rockwood, 1876). The shock was reported to have lasted approximately thirty seconds at Washington and Augusta, Georgia, with two or three aftershocks accompanied by rumbling noises (Rockwood, 1876, Atlanta Constitution, 1875, see Figure 1).

Earthquakes of sufficient intensity to be felt with epicenters in east-central Georgia have not been reported since the 1875 earthquake. However, following the installation of the ATL World Wide Standard Seismograph Station at Lovejoy, Georgia in 1963 at least twelve events have been identified which have epicenters in the central Savannah River area (C.S.R.A.). Nine of these events have computed local magnitudes (M_L)

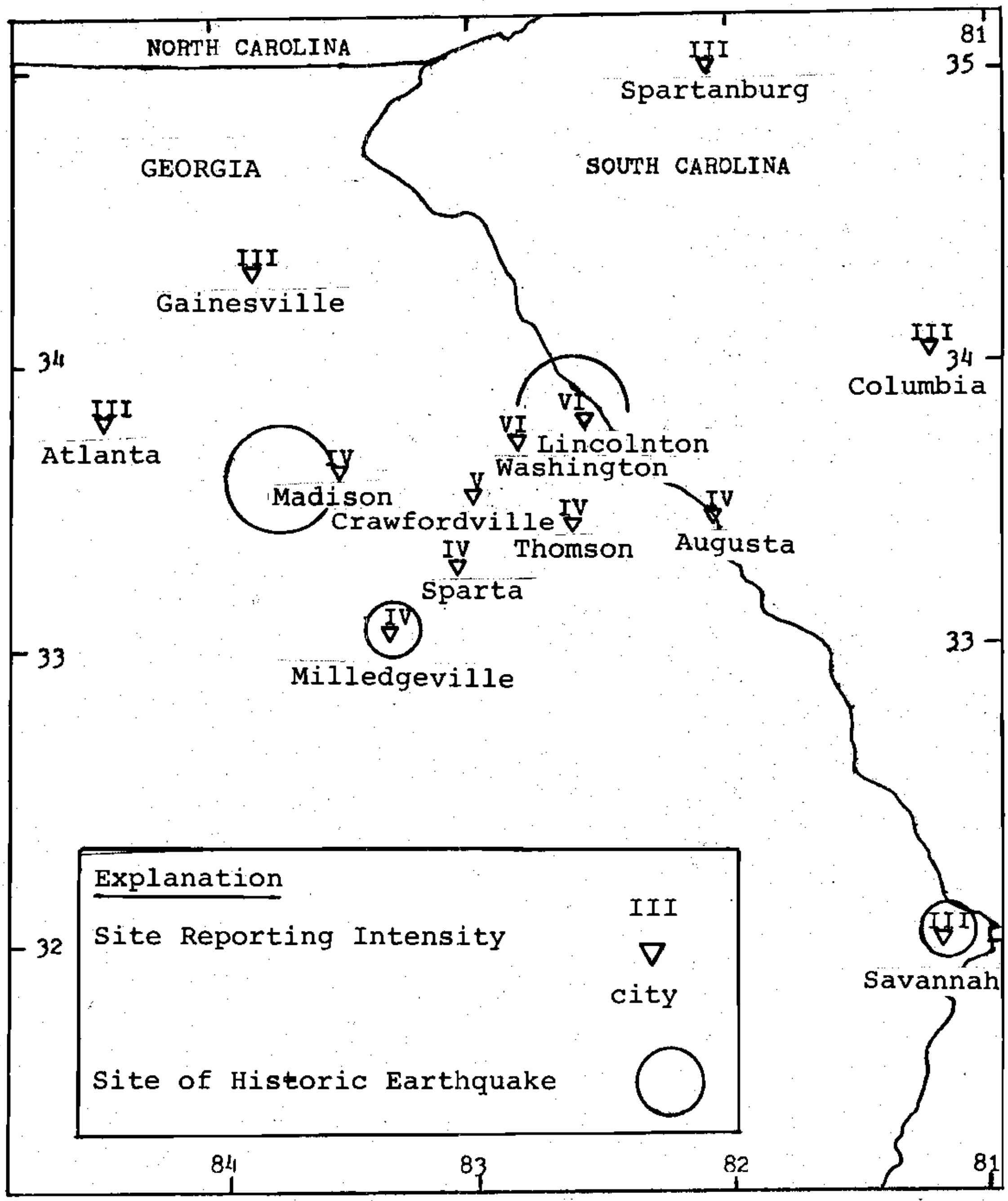


Figure 1. Intensities of the November 1, 1875 Earthquake and Epicenters of Earthquakes of Intensity V or Greater in Georgia (Rockwood, 1876; Atlanta Constitution, 1875).

greater than 3.0. Local magnitudes were computed by using the equations in Nuttli (1973). In addition to these twelve events, several smaller events have occurred, notably a swarm of nearly forty microearthquakes during the summer of 1969 (Long, 1974). Three of the twelve events took place in early to mid-May, 1969. The largest magnitude event ($M_L = 3.4$) occurred on May 18, 1969 at 10:54 GMT and a second, slightly smaller event ($M_L = 3.2$) occurred two minutes later.

During the course of this study two events were recorded by the ATL WWSSN station as well as stations at McMinnville, Tennessee (CPO) and Jenkinsville, South Carolina (JSC). The first of these events occurred with a local magnitude of 3.3 on October 8, 1973 at 13:38 GMT and was recorded at ATL and CPO. Another event with a local magnitude of 2.7 occurred on February 13, 1974 at 6:56 GMT and was recorded at all three stations. Because of the azimuthal distribution of stations this most recent event is considered to be the most reliably located of the earthquakes occurring in the Clark Hill area.

Although at one time the suspected cause of the smaller events, quarry activity has been ruled out on the basis of trace amplitudes, times of occurrence and location of epicenters. Quarries near Elberton, Georgia which explode the equivalent of 10,000 pounds of explosive produce deflections of about one millimeter at a displacement gain of 50,000 on the ATL records. Charges of up to 40,000 pounds of explosive detonated near Camak, Georgia at a distance of 160 km from ATL produce only slightly larger deflections which consist principally of surface waves. No other operations of large size have been identified in close proximity to the reservoir. The larger earthquakes, however, indicate the equivalent of explosive in excess of 70,000 pounds in the source area (long, 1974).

Bollinger (1972) has postulated a northwest-southeast trending zone of seismic activity, the southwest fringe of which extends along the Georgia-South Carolina border (see Figure 2). The most frequent occurrence of seismic activity lies along the central portion of the zone extending northwest from Charleston through Greenville, South Carolina. Other structures or trends which lie in the same NW-SE orientation are the gentle basement warpings of the Cape Fear and Ocala structural arches and the Triassic diabase dikes. However, any direct relationship between these structures and Southeast seismic activity has yet to be proven.

The geology of the Clark Hill Reservoir area has been investigated by only a few individuals but these have made remarkable progress in the mapping and identification of structural units (Crickmay, 1952; Austin, 1965; McLemore, 1965; Fouts, 1966; Hurst et al., 1966; Paris, 1974; and O'Connor et al., 1974). Recommendations have been made for the use of geophysical methods in conjunction with conventional mapping techniques (Sundelius, 1970). Geophysical methods might aid in resolving the structures and distributions of lithologic units in the Piedmont province. Except for sparse gravity data and seven refraction profiles (Woollard et al., 1957) geophysical investigations are unknown for this area.

Both geophysical and geological techniques are employed in this study. In the following sections the results of these investigations are described and certain possibilities which may explain the observed seismic activity in the Clark Hill Reservoir area are examined.

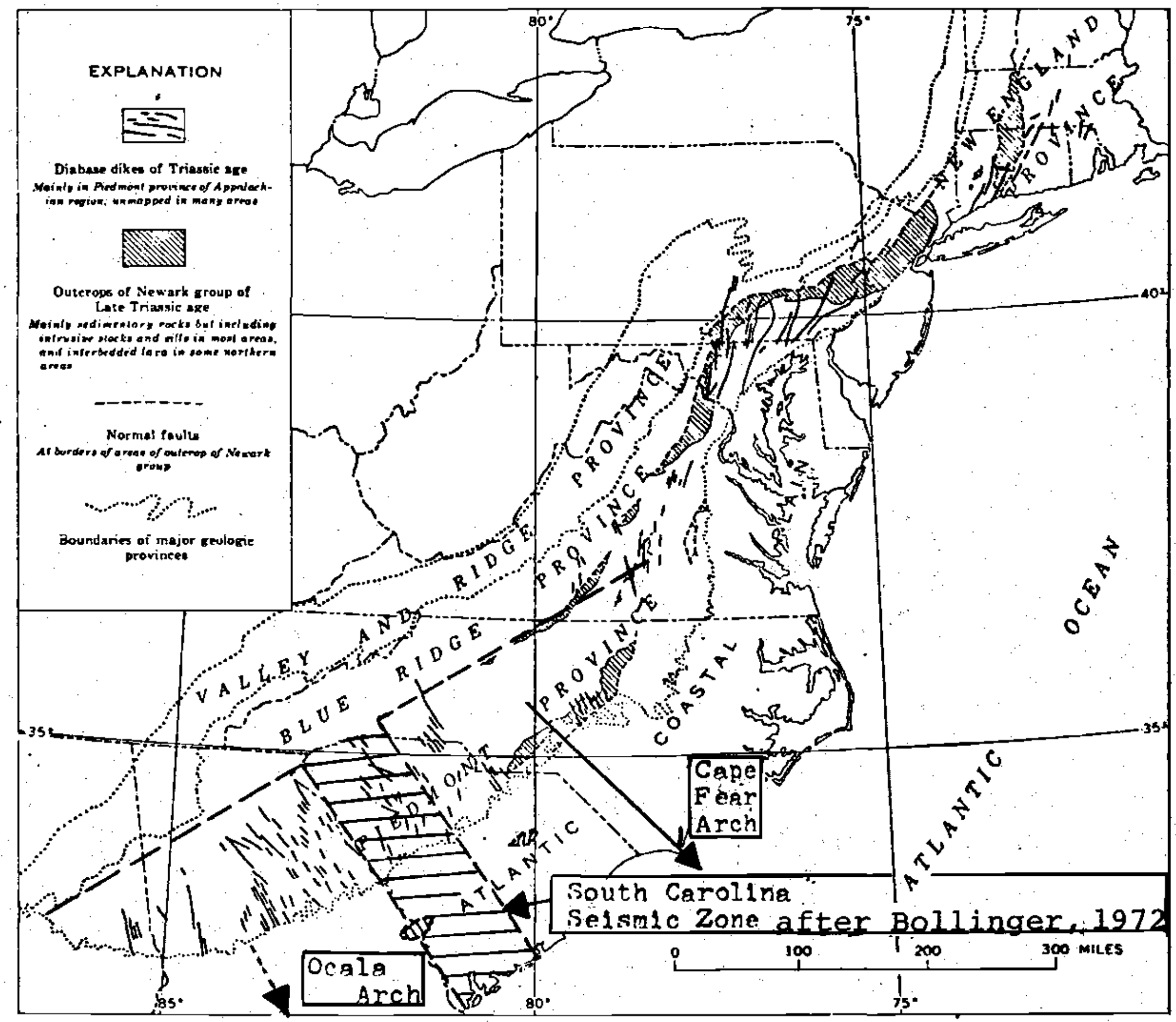


Figure 2. Regional Northwest Trending Structures and the South Carolina Seismic Zone (Sketch map after King, 1961; Ocala Arch in Florida).

CHAPTER II

GEOLOGY OF THE CLARK HILL RESERVOIR AREA

Piedmont Province and Geologic Setting

In east-central Georgia the Piedmont Province is bounded to the northwest by the Brevard shear zone and the Blue Ridge Province and is bounded to the southeast by the Atlantic Coastal Plain Province (see Figure 2). The coastal plain sedimentary sequences onlap the metamorphic rocks of the Piedmont Province (Figure 3). The metamorphic rocks comprise the geologic basement of the coastal plain sedimentary sequences. Metamorphic rocks are exposed in the Piedmont Province and are divided on the basis of lithology into NE trending, linear belts.

The rocks of the Clark Hill Reservoir area lie wholly within the Piedmont Province and are of metamorphic and igneous origin and of Paleozoic to Precambrian age. Figure 3 indicates the structural belts of the Piedmont Province in east-central Georgia. Northwest trending Mesozoic dikes cross the belts and possess strong local magnetic and gravity anomalies (Rothe, 1973). Basin structures of Triassic age and associated sedimentary fill are also found within the Piedmont Province and beneath the Atlantic Coastal Plain Province. The Dunbarton Triassic Basin lies southeast of the Clark Hill area beneath the Atlantic Coastal Plain sedimentary rock sequences and follows the trend of the basement structure (Marine, 1973).

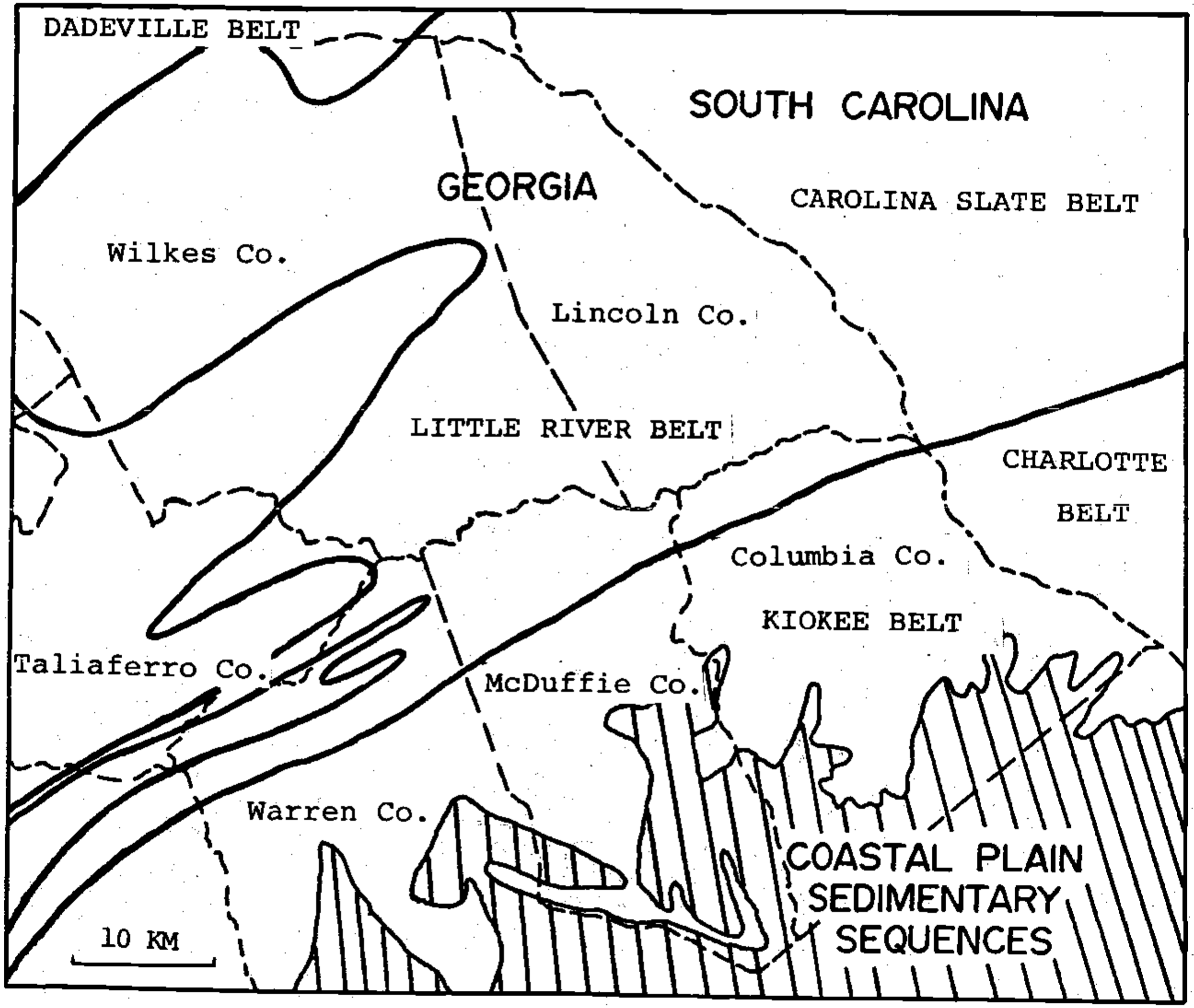


Figure 3. Belts of Crystalline Metamorphic Rocks in East-central Georgia (The Little River Belt and the Carolina Slate Belt are the same but given different names in South Carolina and Georgia).

Description of Lithologic Units of the Clark Hill Reservoir Area

Introduction

The metamorphic complex of east-central Georgia includes portions of the Little River, Kiokee, and Dadeville belts as defined by Crickmay (1952). The Little River belt is the southernmost extension of the Carolina Slate belt into Georgia and underlies Lincoln County and parts of Columbia, McDuffie, and Warren Counties in Georgia (Figure 3). The Kiokee and Dadeville belts are extensions of the Charlotte belt into Georgia and they border the Little River belt to the southeast and northwest, respectively. The Dadeville belt differs from the Kiokee belt principally in the quantity of intrusive bodies present. The geologic map of the Clark Hill Reservoir area (Figure 4) is compiled from Central Savannah River Area geologic maps by Hurst, Crawford, and Sandy (1966). This map shows the extent and configuration of the major lithologic units which comprise the metamorphic belts of the area.

The principal lithologic unit to the south of the reservoir area is a hornblende-biotite gneiss which is locally intruded by pods of biotite-muscovite granite. The southern reservoir area in the Little River vicinity is underlain by metasediments of volcanic origin, metavolcanics, schists, and gneisses which Crickmay (1952) has termed the Little River Belt. The lithologic units in the area of interest for the seismicity investigation and gravity measurements lie principally within the Little River Belt. The principal lithologic units from north to south in Lincoln County are the metadacite, the hornblende-biotite gneiss, the quartz-sericite schist, the phyllite and metavolcanics, and the "button"

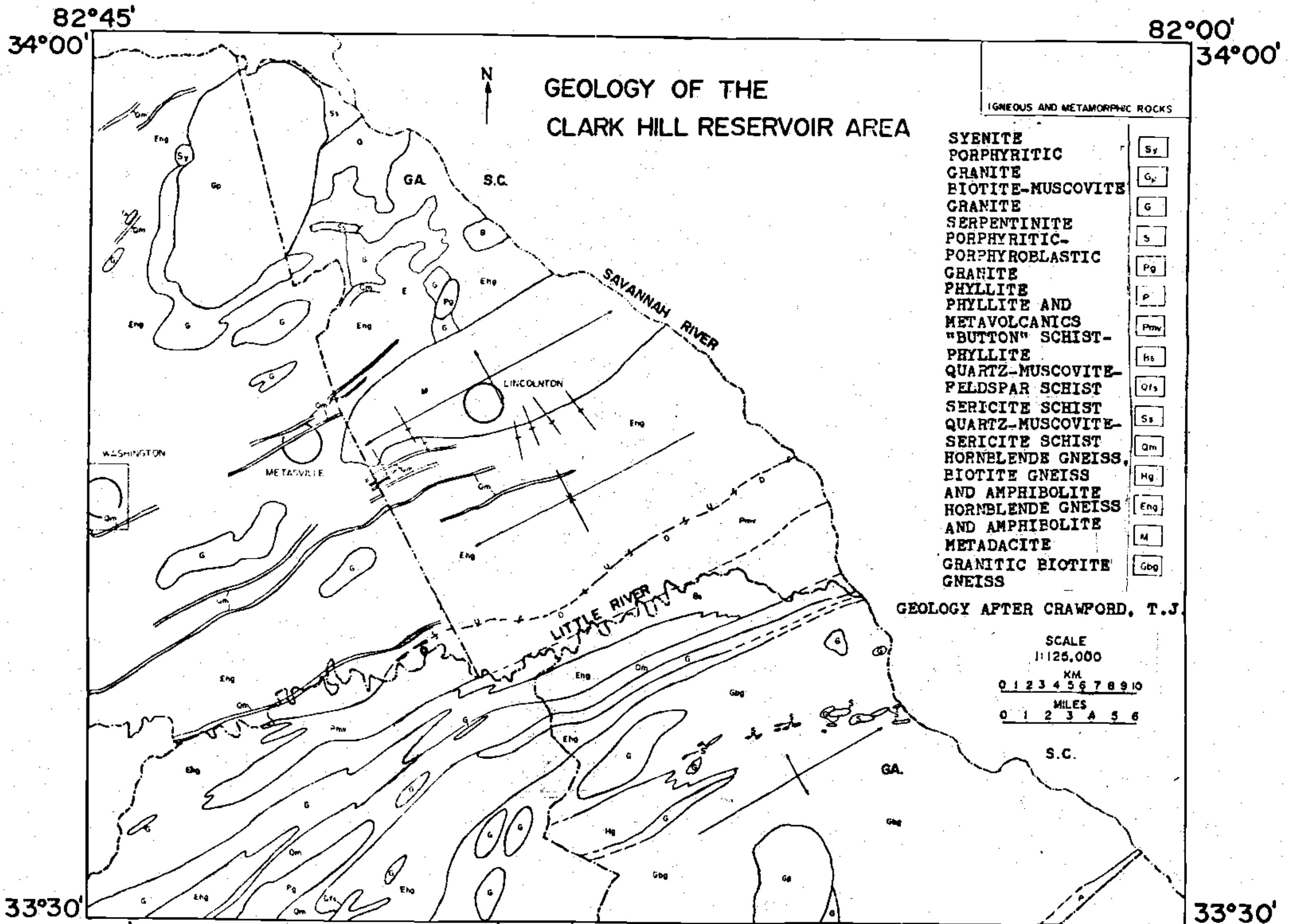


Figure 4. Geologic Map of the Clark Hill Reservoir Area.

schist-phyllite as well as the igneous and meta-igneous intrusive units.

Metadacite Unit

A coarse grained, light colored, metadacite strikes NE across the central portion of Lincoln County in Georgia and terminates to the east-northeast near McCormick, South Carolina (Bell, 1973). The maximum width or minor axis of the metadacite is about seven kilometers near Lincolnton, Georgia with an ENE trending major axis of about thirty kilometers length. Composition of the metadacite unit is predominantly oligoclase feldspar and blue-gray quartz (Bell, 1973). Weathering of the metadacite produces a characteristic soil containing blue-gray quartz fragments which facilitate geologic mapping. Meta-sediments and gneisses surround the metadacite. Blue quartz content of the meta-sedimentary units diminishes with distance from the metadacite unit (Bell, 1973) indicating that the unit is the most probable source of the original sediments. The metadacite appears to be a shallow intrusive or dome which was emplaced near the surface during the early Paleozoic or late Precambrian.

Basic dikes which lace the metadacite intrusive have been metamorphosed to amphibolite assemblages. These units probably serve to increase the effective density of the metadacite owing to their abundance and pervasive character. Fouts (1966) has examined these dikes and found them to consist of roughly 60% hornblende, 30% plagioclase, 7% epidote, and 3% accessory minerals.

Hornblende Gneiss--Biotite Gneiss--Amphibolite Unit

Gneisses and amphibolite units overlie the metadacite unit and are found in north, central, and south-central Lincoln County. These interlayered lithologic units are usually fine grained with lenses of biotite, hornblende or epidote present (Crawford, Hurst, and Ramspott, 1966). The hornblende gneiss of the Little River series differs from other hornblende gneisses in Georgia in that it appears to be of coarser texture. These gneisses are thought to have originated from the metamorphism of diorite sills intruded into the Little River Belt (Crawford, Hurst, and Ramspott, 1966).

Quartz--Sericite Schist Unit

The quartz-sericite schist unit crosses Lincoln County in thin bands and is composed predominantly of muscovite and/or sericite mica with a white to grey appearance in fresh exposures. Weathering of this unit produces a red residuum exposing small amounts of pyrite and magnetite in outcrops which vary from 30 to 150 feet in thickness. These units appear to have originally existed as beds of volcanic ash which were either subaerially or subaqueously lain and subsequently metamorphosed.

Phyllite and Metavolcanic Unit

Phyllite and fine to medium grained metavolcanics are found in southern Lincoln County forming a band one to two miles in width. This unit lies along the north shore of the Little River and contains a mafic unit approximately 300 meters thick. The phyllite is dark grey to black when fresh and weathers to shades of pink, buff, or light grey (Crawford, Hurst, and Ramspott, 1966).

Extrusive andesites and feldspathic metavolcanics resembling ignimbrites also occur in the phyllite and metavolcanic belt and appears to be more silicious than the other metavolcanic units in the area. Pegmatites and large quartz dikes are found scattered throughout the reservoir area, usually associated with the granite intrusives. The largest quartz dikes, possessing ENE trends, lie within the metavolcanic unit which coincides with the gold belt of the Little River area.

"Button" Schist--Phyllite Unit

"Button" schist is a contorted sericite schist unit which contains stringers of quartzite, and outcrops along the Little River arm of the reservoir. Readily identifiable by the pink coloration and numerous muscovite buttons, the unit strikes ENE along the northern boundary of Columbia County and across the Savannah River into South Carolina. This material, which exhibits strong cataclastic deformation and flowage, defines a possible shear zone approximately one kilometer wide and lies in close proximity to a fault zone crossing southern Lincoln County and extending to Lake Murray, South Carolina.

Meta-igneous and Igneous Units

The metamorphic complex of the Clark Hill Reservoir area has been subjected to extensive plutonism which along with subsequent metamorphism has produced granites, granite-gneisses, and altered mafic intrusives. The basic intrusives are principally basalts which have been subsequently altered to amphibolite by metamorphism. The basic dikes in the metadacite and gabbro comprise the mafic intrusives. The acid intrusives are granites, granite-gneisses, and syenites which are represented by the Danburg, biotite-muscovite, and porphyritic granites.

Gabbro intrusives are characterized by their typically low elevations which reflect their high susceptibility to weathering. Composition of the gabbroic material is calcic plagioclase and pyroxene. These minerals exist as coarse crystals which are occasionally found altered to hornblende (Crickmay, 1952). This gabbro which is usually metamorphosed is not observed in the immediate reservoir area. A few small ultramafic serpentinites are found in Columbia County (Georgia) possessing an ENE trend and extending into South Carolina. The serpentinites have probably resulted from the degradation of peridotites.

A small outcrop of prophyritic granite occurs in north-central Lincoln County. The body appears to be roughly elliptical in plan, but work is needed to define the full extent of the body. More massive exposures of this unit occur in Warren County at the Martin Marietta quarry near Camak, Georgia.

The Danburg porphyritic granite is perhaps the youngest of the granites in the Clark Hill area. It outcrops on the Lincoln-Wilkes County boundary. The elliptically shaped body of the Danburg granite covers an area of approximately 130 square kilometers and intrudes the Little River series. Mineral content is uniformly feldspar phenocrysts enclosed in a feldspar-quartz-biotite groundmass (Crawford, Hurst, and Ramspott, 1966). Another large intrusion of the Danburg granite occurs in Columbia County near Appling, Georgia. The Danburg pluton cuts the biotite granite and granite-gneiss lithologic units.

Diabase dikes are found throughout the area with thicknesses seldom greater than 40 feet, strikes within a range of N20^{o}W to N50^{o}W and near vertical dips (Hurst, Crawford, and Ramspott, 1966). The dikes are prominantly jointed and in places are weathered to a residuum only distinguishable by color from the surrounding saprolite. A range of textures is noted in the dikes with pyroxene and labradorite being the chief mineral constituents (Crawford, Hurst, and Ramspott, 1966).

Stratigraphic Succession

The stratigraphic succession of the metamorphic rocks of the Piedmont Province is taken from Overstreet and Bell (1965)(see Table 1). Although the stratigraphic succession and the intrusive sequence for the igneous lithologic units are described for the South Carolina Piedmont Province, they apply as well to the Clark Hill area. The intrusive sequence proposed by Crickmay (1952) for the Piedmont Province rocks agrees well with the ordering of events in the Bell-Overstreet system and the succession of lithologic units identified by Hurst, Crawford, and Sandy (1966) for the Clark Hill area.

The geologic belts proposed by Overstreet and Bell are based largely on the distribution of residual soils from maps prepared by the U.S. Department of Agriculture. These soils are distributed in belt like configurations determined by the strike of the underlying rock. The belts of interest are the Carolina Slate belt which is equivalent to the Little River belt in Georgia and the Charlotte belt which contains sequences stratigraphically equivalent to those of the Dadeville and Kiokee belts previously described.

Overstreet and Bell (1965) have identified lower, middle, and upper stratigraphic sequences for the Piedmont Province rocks, each of which was deposited in a subsiding basin at or near a continental margin. Separating each of these sequences is an unconformity. In Georgia the contact between the lower and middle sequences corresponds to the contact between the Little River series and the gneisses of the Kiokee and Dadeville belts.

The lower sequence consists of meta-sedimentary and meta-igneous

Table 1. Inferred Stratigraphic Succession and Sequence of Igneous Episodes for the Lithologic Units in the Clark Hill Area--Piedmont Province (adapted from Overstreet and Bell, 1965)

Presumed Geologic Age	Sequences of Sedimentary and Pyroclastic Rocks	Carolina Slate Belt--Little River Series	Charlotte Belt--Dadeville--Kiokee Belts
Permian	Intrusive Episode C	Syenite pegmatite	Syenite pegmatite
Permian		Syenite	Syenite
	Intrusive Episode C	Gabbro, Pyroxenite	Gabbro, Pyroxenite,
Permian		Norite	Norite
and Carboniferous		(Circular Plutonic Intrusives)	
		Porphyritic granite and biotite-muscovite granite	Porphyritic granite and biotite-muscovite granite
Carboniferous	Upper Sequence	Mica Gneiss	Argillite
UNCONFORMITY			
	Middle Sequence		
	Intrusive Episode B	Metamorphosed Mafic Dikes	Metamorphosed Mafic Dikes
Devonian through		Mica gneiss	Argillite
Ordovician	Middle Sequence		Muscovite Schist
			Amphibolite
UNCONFORMITY			
	Intrusive Episode A	Porphyritic granite and gneissic grano-diorite in S.C.	Not recognized
Cambrian and Late Precambrian		Granitoid Gneiss	Granitoid Gneiss
UNCONFORMITY (UNEXPOSED)			
Precambrian	Basement		

rocks which are exposed in the Charlotte belt (Dadeville in Georgia). Originally these rocks consisted of graywackes, arkoses, shales, and pyroclastics, but they have been altered to granitoid gneiss and migmatite. This sequence rests unconformably on Precambrian basement rocks of the Piedmont Province which are assumed to be ancient plutonic gneisses and schists much like the rocks of the Blue Ridge Province (King, 1961).

The middle sequence is composed of graywacke, tuffaceous argillite and lavas, and tuffs. Rocks of this sequence are arched into broad folds represented by the Little River belt in Georgia. Metamorphosed lavas are common near the base of the middle sequence along with felsic flows (i.e., metadacite). The upper sequence consists of intercalated mafic lavas and argillites (i.e., phyllite-metavolcanic unit). Crickmay (1952) observed that the Little River series may be the equivalent of the Arvonia or Quantico slates of Virginia which are thought to be of similar origin.

Intrusive Episodes and Metamorphic Events

Three major episodes of igneous intrusion are apparent from the crosscutting relationships which exist in the Piedmont Province. These episodes occurred during the later stages of each stratigraphic sequence (Overstreet, 1970). Episodes have been defined by radiometric dating and can be correlated with the intrusives of the Clark Hill area. Episode A included the intrusion of lithologic units which were later metamorphosed to gneisses and are not observed in the immediate reservoir area. Episode B intrusives which are overlain unconformably by rocks of the upper sequence are felsic intrusives and mafic rocks which are represented in the Clark Hill area as metamorphosed Little River series dikes and the metagabbros previously discussed. These rocks underwent later metamorphism which degraded them to a hornblende-epidote facies. The intrusives of episode C are discordant granite plutons which intrude the Carolina Slate belt and the Charlotte belt. These occur as pegmatites or syenites and they are represented in the Clark Hill area by the Danburg granite and the biotite-muscovite granite. Episode C plutons are often structurally controlled and follow the gross trend of Piedmont Province structure. Characteristically they exhibit an oval shape as do many of the granites of the reservoir area. The NW-SE trending diabase dikes of Triassic age culminate the intrusive events and crosscut all other sequences and intrusives.

Three major metamorphic events have occurred in the Piedmont Province in addition to the original metamorphism of the Piedmont basement rocks (1100 m.y.b.p.). These metamorphisms are of late Precambrian or early Cambrian age (550 m.y.b.p.), Ordovician age (450 m.y.b.p.), and Carboniferous to Permian age (260 m.y.b.p.) (Overstreet, 1970). Retrograde metamorphism has altered the mineralogy and often mutilated the original features; however, the principal metamorphic event appears to have occurred in the Ordovician (Taconic). These dates are based on lead-alpha radiometric age determinations which may not be accurate. The few reliable radiometric dates along with the discovery of a trilobite in the slate belt rocks of North Carolina have confirmed an age for the Carolina Slate Belt (and therefore the Little River series) as early Paleozoic.

Structural Geology and Global Tectonics

The regional trend of the observed structures in the Clark Hill area is ENE, consistent with the trend of Piedmont Province structure, and with most units exhibiting steep dips to the southeast. Occasionally, however, lithologic units will show northwest dips indicating overturned units or folds. The granitic-biotite gneiss forms the axis of a large anticlinal structure which crosses Warren, McDuffie, and Columbia counties in Georgia (see Figure 4). The metadacite unit of the Little River series is also an anticlinal structure which appears to be doubly plunging NE-SW.

Stream and river lineation patterns (Figure 5) reveal a strong structural control which is principally due to jointing. The most common systems of joints appear to be oriented NE, NW, ENE, and NNE. These stream patterns have proven useful in the detection of faults in the area (O'Connor et al., 1974).

Although fault systems are poorly defined in the reservoir area, several prominent silicified zones have been mapped, and NW trending faults of post Cretaceous age recently have been shown to exist in the Piedmont Province rocks (O'Connor et al., 1974). The largest fault in the area is the Lake Murray fault which has been mapped into Georgia by Crawford where it strikes NE across southern Lincoln County. Offsets of quartz veins, pegmatites, and basic dikes indicate that small movements have taken place at several locations along the fault (Crawford, Hurst, and Ramspott, 1966).

Six faults with strike ranging from N12^{o}W to N40^{o}W have recently been identified in Lincoln County. These show displacements ranging from less than 200 feet to greater than 2000 feet (Paris, 1974). These faults cross the metadacite unit and extend through the Little River series phyllites and gneisses. Four of the faults show right lateral displacement and two

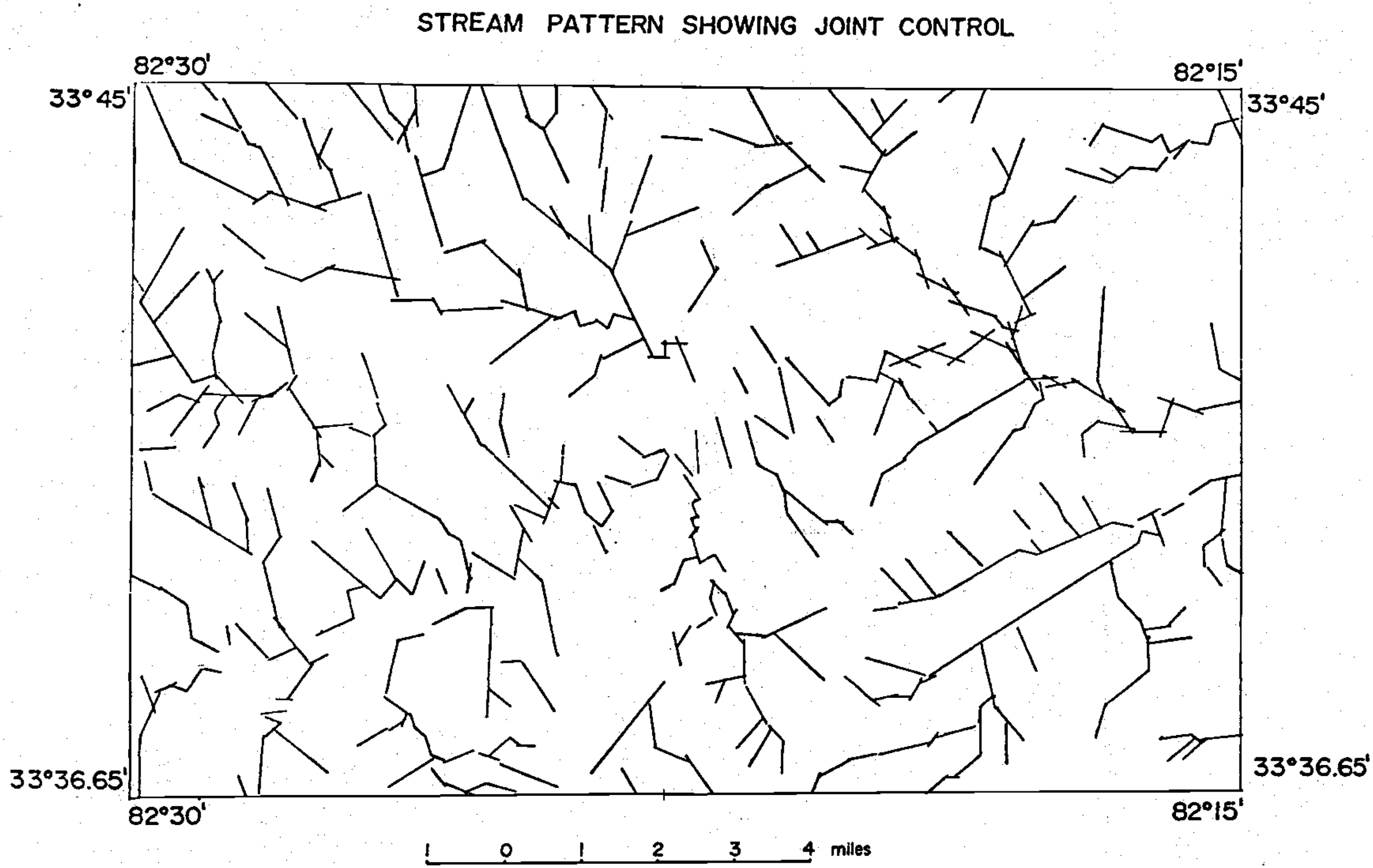


Figure 5. Stream Pattern Showing Structural Control in the Little River Area.

show movement which indicates left lateral displacement (O'Connor et al., 1974). Exposures near Belair, Georgia indicate that these NW striking faults offset formations of late Cretaceous age (Tuscaloosa) (O'Connor et al., 1974).

King (1961) ascribes the orientation of the numerous diabase dikes found within the Piedmont Province to stress patterns within the Piedmont existing during the formation of these dikes. More recently Rogers (1970) and May (1971) have suggested that the formation of these dikes is due to stresses imparted to the southeast region during the separation of North America from South America and Africa. The relatively greater abundance of Triassic diabase dikes in the southern Piedmont Province than in the northern Piedmont Province (Figure 2) may also imply that greater regional tension was developed in the Georgia-South Carolina area as a result of proximity to the suture at the time of formation of these dikes.

The shear zone and proximity of serpentinite bodies along with the metamorphosed volcanic pile illustrate some interesting similarities to present day island arc systems in the Pacific. Paired metamorphic belts which resemble those observed in the east-central Georgia Piedmont Province have been used as evidence for ancient subduction zones (Miyashiro, 1973). Similarities are also noted to the model proposed by Coats (1962) for trench areas. The volcanic pile to the northwest of the shear zone and the heavy igneous intrusion of the rocks to the northwest indicate a source of siliceous and mafic magmas which were possibly supplied by an underthrust lithospheric plate dipping to the northwest. The "hot" metamorphic axis (Hurst, 1970) which arcs across central Georgia and into South Carolina roughly follows the trend of the shear zone which crosses the Savannah

River into South Carolina. This metamorphic belt is contemporaneous in age with the Appalachian orogeny as indicated by radiometric dates of approximately 265 m.y. within the belt. This should indeed provide an estimate of a lower bound for an age on plutonism due to digestion of the descending plate if the plate is accepted as the material source for the acid intrusives.

Flexuring of the crust at the point of contact possibly produced a doming of the area north of the subduction zone and subsequent extrusion of acid volcanic flows and injection of serpentinites like those noted by Hess (1955) and later by Coleman (1971). The arcuate configuration of the shear zone is analogous to that of island arc systems of the Pacific which exhibit the same geometric configuration, with the underthrust lithospheric plate subducting from the concave side of the arc. This evidence, along with the presence of the metamorphosed pile of volcanically derived sediments (Little River series), the serpentinite intrusions, and the belt of heavy igneous intrusion, lends strong support to the hypothesis of a lithospheric plate inclined to the northwest and the existence of an island arc system during the formation of this part of the Piedmont Province.

This interpretation of the paleotectonic state of affairs agrees with that recently put forth by Roper and Justus (1973). This hypothesis also agrees with that of Dewey and Bird (1970).

CHAPTER III

GRAVITY MEASUREMENTS

Measurements of the acceleration of gravity were made in the reservoir area in order to determine the Bouguer anomalies for use in a study of density contrasts related to geologic structures. A total of 311 new gravity stations were added to 88 existing data points in the reservoir area. Data were obtained with a spacing of approximately one mile between stations in the central region. These data were then reduced and used to produce a contour map of the Bouguer anomalies (Figure 6). Elevation control was obtained from bench marks (± 0.5 ft), controlled intersections (± 2 ft), and lake pool elevations (± 1.0 ft). Estimates of precision were assigned to the gravity data on the basis of the precision of elevation control and the particular gravity meter used. All stations were located from 7.5 minute or 15 minute topographic maps, or reservoir navigation charts. The precision of these locations is estimated at ± 0.1 km with a corresponding error of ± 0.1 milligal due to latitude effect. Since reservoir levels were helpful in the location of stations as well as in elevation control, many stations were occupied along the reservoir shoreline. Table 9 in Appendix B is a list of base stations occupied or established during the surveys. Appendix B lists the data and describes the methods of data reduction and interpretation. Based on the precision of the total data collection and reduction process, error in the Bouguer gravity anomalies is considered to be less than ± 0.5 milligal.

SIMPLE BOUGUER ANOMALY MAP OF THE CLARK HILL RESERVOIR AREA

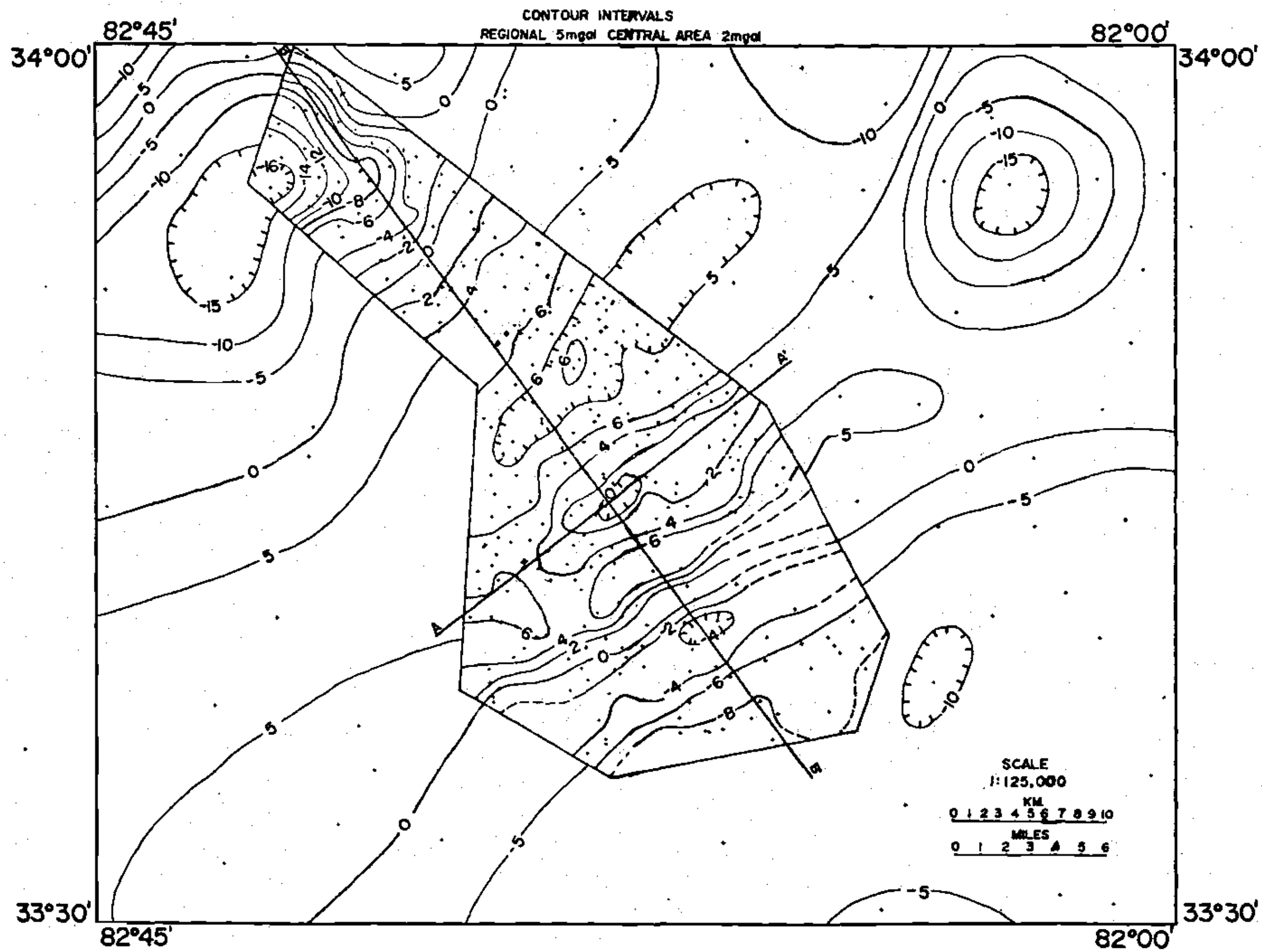


Figure 6. Bouguer Anomalies for the Clark Hill Reservoir Area.

The Bouguer anomaly map is contoured at intervals of two milligals in the central region and at five milligals over the rest of the map. Two milligals is considered to be an appropriate contour interval for data on one mile centers since gradients in the area are on the order of two milligals per mile or less. No significant regional gradient was detected in this area; this indicates that anomalies are caused by density contrasts in lithologic units which have most of their effective mass above a depth of about ten kilometers. The entire area lies principally within a broad gravity high which crosses into South Carolina (Long, Bridges, and Dorman, 1972) on strike with the structure of the Piedmont Province.

A comparison of the mapped geology and the gravity anomalies reveals that several major structural units can be correlated with the observed gravity anomalies. The gravity anomalies were then used to place probable limits on the vertical extent of these structures. To accomplish this, profiles of the observed gravity anomalies were constructed parallel (A-A') and perpendicular (B-B') to geologic structures (Figures 7 and 8, respectively). Geologic models were then generated which not only satisfy the observed gravity anomaly pattern, but also remain consistent with surface control for the geologic structures as provided by the geologic map (Figure 4). This method resolves one of the uncertainties inherent in the interpretation of gravity anomalies and produces realistic models of geologic structures.

Examination of the units proceeding from the NW portion of the reservoir area to the SE and their respective anomalies indicates those lithologic units which are responsible for the most prominent anomalies in the area. The Danburg granite is the source of a -16 milligal anomaly

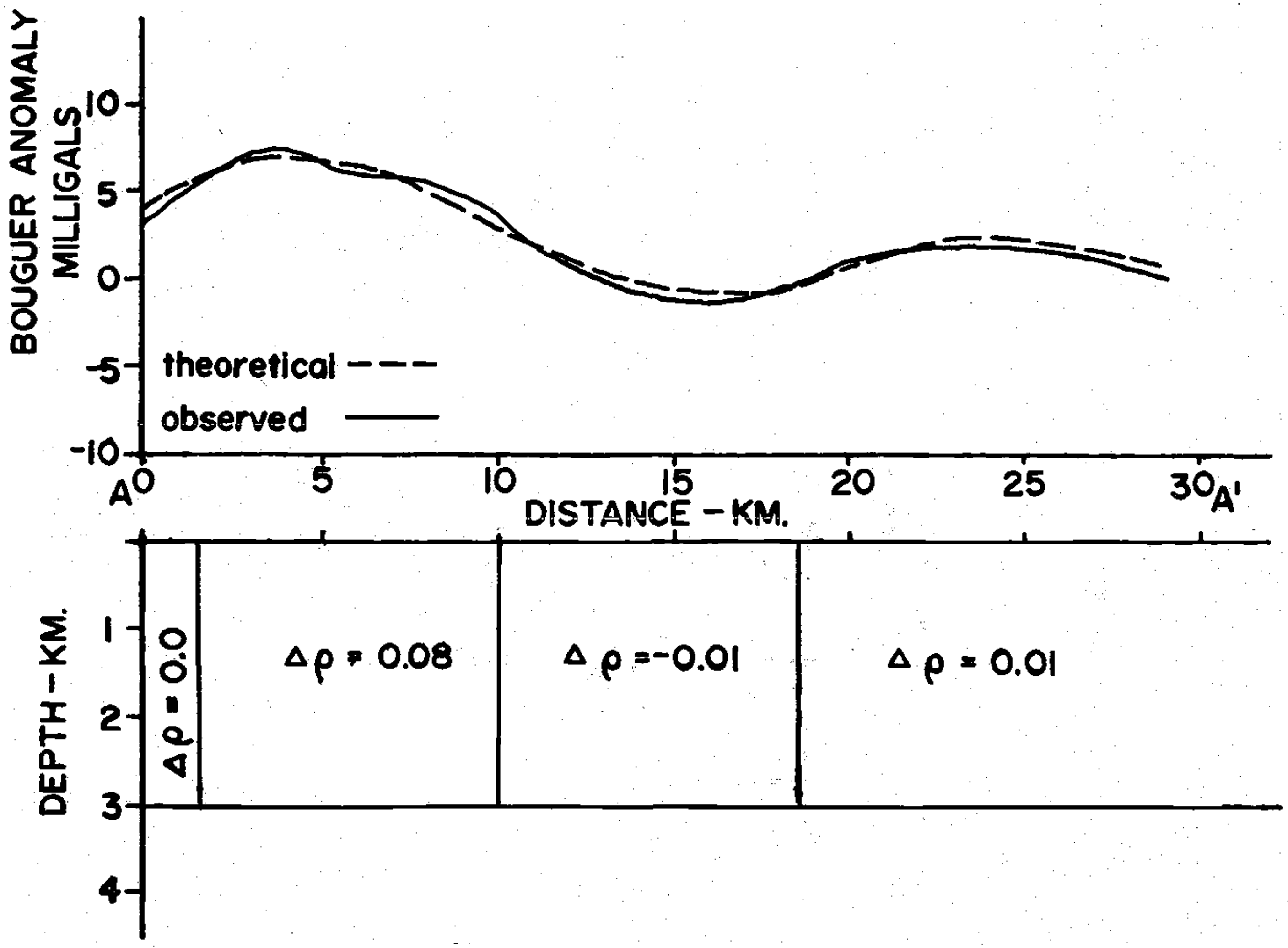


Figure 7. Profile of Low Gravity Anomaly Termination in Southern Lincoln County, Model A-A'.

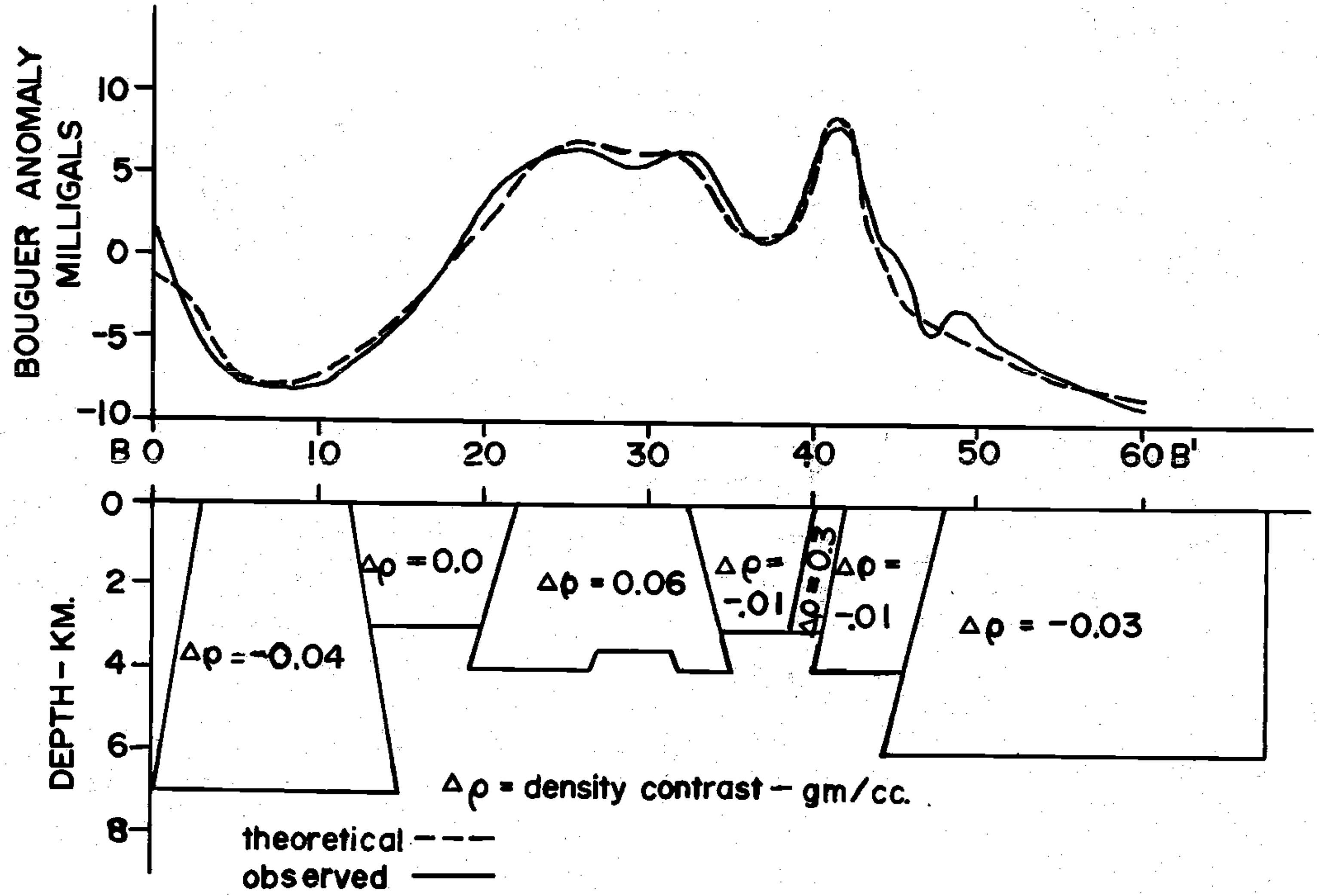


Figure 8. Gravity Profile Transverse to Piedmont Structure, Model B-B', Savannah River.

in northwest Lincoln County. The gravity anomaly indicates a low density intrusive body of large size which extends to a depth of at least 7 km (profile B-B'). In the model a density contrast of - 0.04 gm/cm^3 and body boundaries coinciding with the outcrop dimensions described in Chapter II have been assumed. The metadacite unit crossing central Lincoln County appears to be the source of a 6.5 milligal anomaly which follows the same trend. The anomaly indicates a density contrast of 0.06 gm/cm^3 for this material. Mafic dikes which lace the metadacite increase the observed anomalies and impart a higher density contrast than that expected for metadacite alone. The anomaly is bimodal with a central depression which possibly indicates a thinning of the metadacite in the crest of the structure (see profile B-B').

Another body of exceptionally high density material lies along the north shore of the Little River where its axis parallels the trend of the north shore. The 7.9 milligal anomaly corresponds to a serpentinite member in the phyllite and metavolcanic unit of the Little River series. The serpentinite member has a density of 2.96 gm/cm^3 and produces a gradient of nearly five milligals per mile across the formation.

Transitional Bouguer anomaly values are obtained between the highs and lows produced by the intrusive units. These values are associated with the phyllite-argillite-gneiss which comprises the bulk of the Little River belt. Small lows such as the one immediately south of the reservoir (Figure 6) are associated with elliptical biotite-muscovite granite intrusives. A large circular intrusive of this type produces a - 16 milligal anomaly in South Carolina to the east of the reservoir area. This anomaly is of the same magnitude as that observed for the Danburg intrusive previously mentioned. Another large outcrop of porphyritic granite near Appling, Georgia is also of this same general size and is expected to exhibit an anomaly of similar magnitude when data are acquired in this area.

The area to the south of the reservoir exhibits low anomaly values decreasing to the south with a gradient of about two milligals per mile. These are associated with the granitic biotite gneiss of the Kiokee series which thickens to the southeast toward the axis of the structure.

Deflections of many of the contour lines in the reservoir area are ascribed to the presence of the numerous mafic dikes which transect the area. These deflections are minor and unimportant in terms of gross structure except where major discontinuities are observed. One such discontinuity occurs in the southwest reservoir area just north of the Little River where a northeast trending low is truncated by an apparent offset in the gravitational high. A saddle exists in the seven milligal ridge as well as an observed offset in the anomaly which indicates an apparent right lateral strike slip displacement of over 2000 feet (0.6 km) along a northwest fracture oriented approximately N20W. This feature lies just south of a mapped fault (O'Connor et al., 1974) with similar displacement and may be continuous with that fault.

CHAPTER IV

SEISMIC VELOCITIES FROM LOCAL QUARRY EXPLOSIONS

The average velocity structure of the Clark Hill reservoir area was determined from the arrivals of P and S phases from nearby quarry blasts. Many quarry explosions were recorded during the microearthquake surveys. Instrumentation consisted of two portable smoked paper recorders and a three component tape recorder system. Ten microearthquake recording stations were occupied, hence, explosions were recorded at varying distances from the three active quarries in the area. Events were identified with quarries by their character, and approximate distances which were computed from S-P times assuming a Poisson's ratio of 0.25. Times of S and P were then plotted versus map distance to the quarries from each station, which produced a local travel-time curve for the reservoir area (Figure 9). The method used for local travel-time, though indirect gives reasonable event locations when used to locate independently recorded events. For distances greater than 40 kilometers, a travel-time curve developed for southeastern events (Mathur, 1970) was used.

Table 2 contains a listing of quarry explosions used in construction of the local travel-time curve and charge sizes where known. Three active quarries are located near the reservoir area. The Martin-Marietta quarry near Camak, Georgia explodes between 25,000 and 40,000 pounds of explosive. Events from thie quarry can be identified by the character of the Rayleigh waves on records from short period vertical instruments (Figure 10).

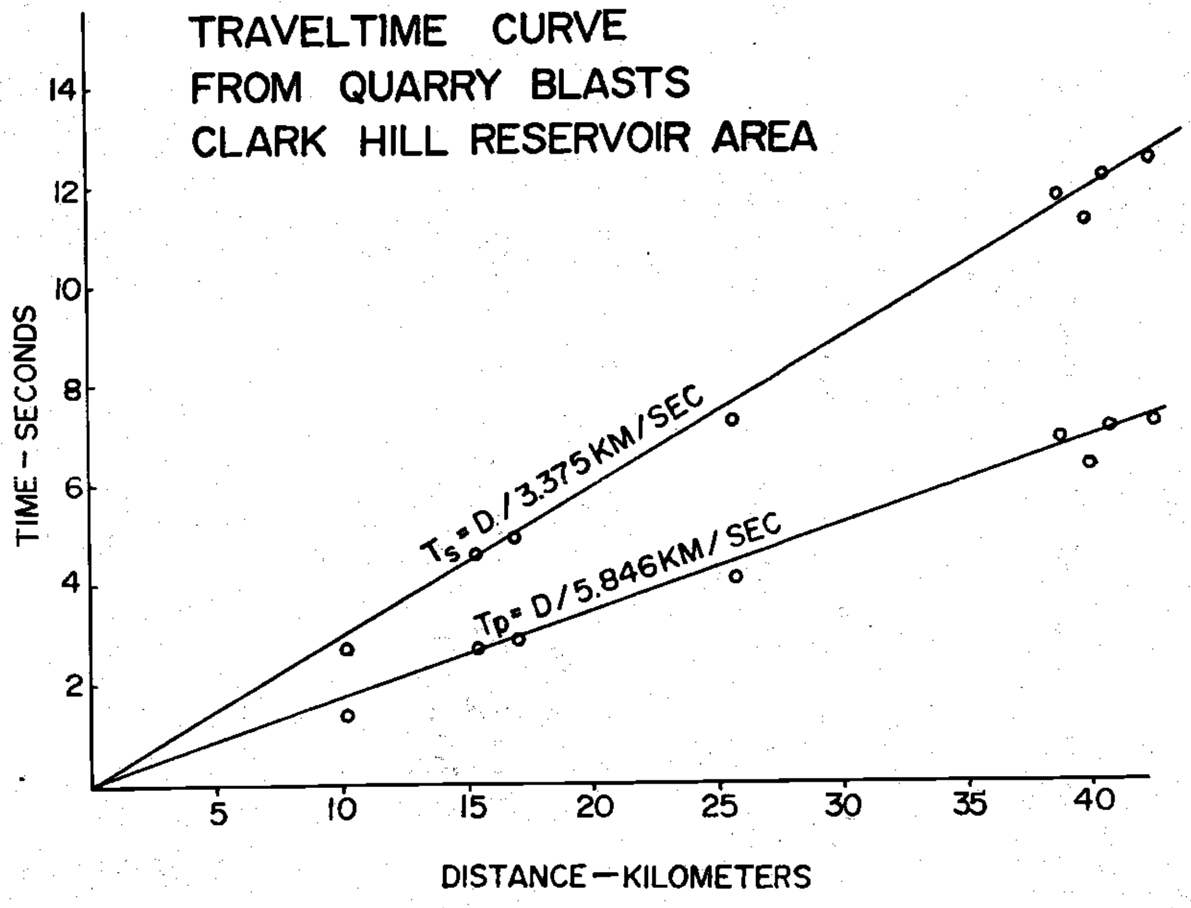
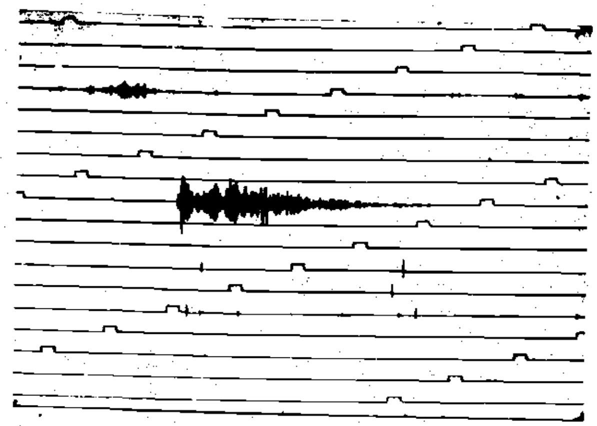


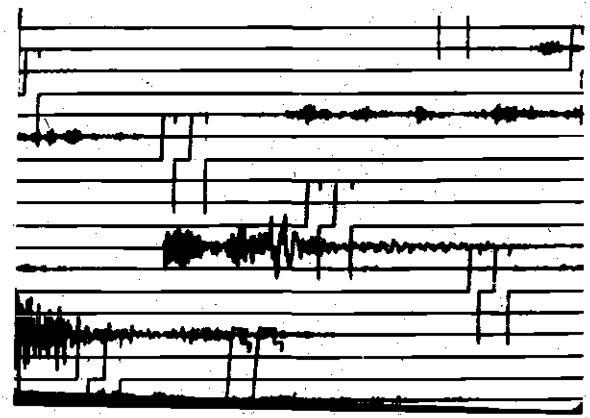
Figure 9. Travel-time Curve from Quarry Blasts.

Table 2. List of Quarry Events Used in Construction of Local TT Curve

Date	Time (GMT)	Station	S-P (Sec.)	Distance (Km.)	Quarry	Charge (Lbs.)
9/17/73	22:17	DBR	4.97	39.97	Camak	37,930
11/13/73	17:33	ESP	1.94	16.43	Graves Mtn.	Undisclosed
11/14/73	22:35	ESP	5.20	42.44	Camak	29,690
11/20/73	22:57	ESP	6.01	48.41	Augusta	Undisclosed
12/11/73	17:39	BBD	2.97	25.85	Graves Mtn.	Undisclosed
12/11/73	17:39	FSH	2.07	17.07	Graves Mtn.	Undisclosed
12/31/73	19:29	CLY	1.36	10.24	Graves Mtn.	Undisclosed
1/01/74	17:48	CLY	5.15	40.73	Augusta	Undisclosed
1/04/74	18:50	CLY	5.19	40.73	Augusta	Undisclosed
1/04/74	18:50	NHC	5.08	38.78	Augusta	Undisclosed
1/04/74	18:50	MSP	3.96	33.41	Augusta	Undisclosed

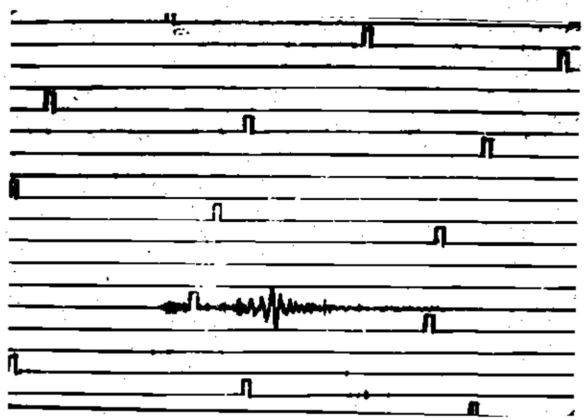


November 20,1973 GMT 22:57



December 11,1973 GMT 17:39

November 12,1973 GMT 22:33



September 17,1973 GMT 22:17

Figure 10. Records of Local Quarry Explosions.

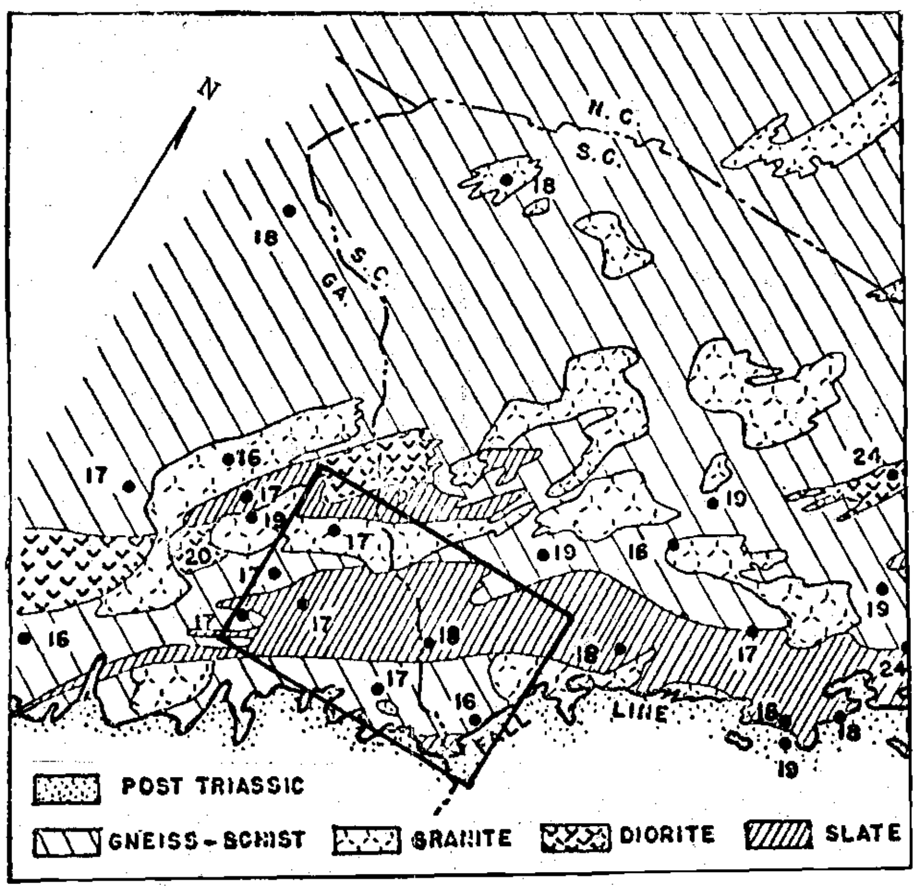
Compressional and shear phases are seldom as distinct as the surface waves except at close range. The quarries at Graves Mountain, Georgia and at Augusta, Georgia typically explode charges of approximately 10,000 pounds or less.

Woollard et al. (1957) have published the results of refraction profiles in the Piedmont Province in which three layers are generally indicated on the basis of the observed compressional velocities. The surface layer is as much as 50 feet thick and indicates a velocity of about 3000 feet/sec. The second layer, usually composed of weathered rock (saprolite), is usually 50 to 150 feet in thickness and typically exhibits velocities ranging from 3000 to 12,000 feet/sec. The deepest layer detected in interpreted as unweathered rock which characteristically exhibits velocities between 17,000 and 22,000 feet/sec. Idealized velocity structure sections have not been found useful since depth to crystalline rock vary dramatically over short distances.

An average velocity of 17,600 feet/sec (5.37 km/sec) was obtained for the schists and gneisses of the Carolina series and an average of 17,400 feet/sec (5.31 km/sec) for rocks of the Carolina Slate belt (Woollard et al., 1957). An average velocity of 17,500 feet/sec (5.34 km/sec) is therefore assumed for compressional waves in surface rock materials at distances under 1000 feet (Figure 11).

Dorman (1972) has suggested that velocity varies as a function of azimuth. For near events, however, any reasonable azimuthal variation was considered to be too small to generate measurable time variations. This was substantiated by calculating the time variation as a function of

RELATION OF SEISMIC VELOCITIES
TO PIEDMONT LITHOLOGY



• SEISMIC STATION
VELOCITY = 18 x 10^3 FT/SEC

Figure 11. Relation of Seismic Velocities to Piedmont Lithology (According to Woolard *et al*. 1957).

azimuth for a 5.8 km/sec crust with a maximum variation in velocity of ± 0.1 km/sec at 90 degrees. This produces a maximum time difference of ± 0.09 seconds at a distance of 30 km which is within the precision realized by the smoked paper recorders (± 0.1 sec).

CHAPTER V

RECENT SEISMICITY OF THE CLARK HILL RESERVOIR AREA

Since the installation of the ATL World Wide Seismograph Station at Lovejoy, Georgia, 12 events ranging in local magnitude from 2.6 to 3.6 (Table 3) have been identified with epicenters in the Clark Hill reservoir area. Due to the sparsity of recording stations in the southeastern United States and relying on poorly established local travel-time curves, Long (1974) initially assigned this activity to the northern extremity of the reservoir area. Subsequent reexamination of these events has indicated that their epicenters are located in central and southern Lincoln County, Georgia. Travel-times associated with the stations northwest of the Appalachians, as well as refraction of surface phases along the structural trend of the crystalline rocks, indicate epicenter locations too far to the north.

Records for the various months listed in Table 4 were examined in order to identify all events recorded during those months. All events listed have local magnitudes greater than $M_L = 2.0$ which appears to be the threshold at which P and S phases are distinguishable at the ATL station. Numerous events of smaller size were found in which the surface waves exhibit the character associated with events locating in the Clark Hill area, but which were not large enough to definitely show P and S phases. Many of these events are suspected to have originated in the Clark Hill area, in which case they would represent microearthquakes of local magnitude less than 2.0.

Table 3. Phase Amplitudes and Computed Magnitudes for Events at Clark Hill

Event	P (mm)*	S (mm)*	R (mm)*	M_L**
2/13/74	No vert.	No vert.	No vert.	+ 2.7
10/08/73	1.0	++ - 7.3	12.5	3.3
4/26/71	0.5	- 1.1	3.2	2.7
4/16/71	0.5	- 6.6	13.8	3.3
5/18/69	2.2	- 3.9	9.5	3.2
5/18/69	3.3	- 7.2	14.5	3.4
5/09/69	2.8	- 5.6	11.1	3.2
4/07/65	5.1	-11.8	21.5	3.5
4/06/65	0.5	- 1.0	2.6	2.6
12/29/64	0.66	- 5.0	10.5	3.2
12/28/64	2.8	- 7.7	5.5	2.9
3/07/64	3.8	-18.1	25.4	3.6
10/07/63	2.5	- 6.5	14.4	3.4

+ estimated from EW trace of surface wave

++ maximum amplitude is downward deflection

* amplitudes corrected to a WWSS network displacement magnification of 50,000

** M_L computed from : $M_L = 3.75 + 0.90\ (\text{Log}\ \Delta) + \text{Log}\ (A/T)$ (Nuttli, 1973)

Table 4. List of ATL Records Examined for Events

Year	Months	No. of Events	2.5
1974	All	1	1
1973	All	1	1
1972	All	0	0
1971	March-April-May	2	2
1969	April-August	40	3
1965	April	2	2
1964	March-April, December	3	3
1963	October	1	1

By utilizing S-P times and the now fairly well established local P wave velocity function for events recorded at ATL, distances relative to the station were computed for event epicenters (Table 5). These relative distances provide good initial estimates of distances to epicenter locations along an arc through the Clark Hill area. The ATL station was chosen as the reference station in the location of these events, because it is the closest station which provides continuous recording. Data available from any other seismic stations that recorded an event were then used to fix the epicenter as precisely as possible on an arc.

An attempt was made to relocate some of the events which were reliably recorded at ATL (see Appendix A). In order to accomplish the relocations a typical event was selected which was well located based on data from three seismic stations (May 9, 1969). Several events were selected which covered the dates and variation in S-P interval time observed from Table 5. These events (see Table 6) were compared by phase cross-correlation. Seismic traces of events recorded at ATL were digitized at 0.1 second intervals and individual P and S phases cross-correlated with the May 9, 1969 event in order to determine variations in S-P time which would reveal systematic deviations in epicenter locations. P and S arrival time differences between events were computed by measuring time differences between the peaks in the correlation functions for each phase respectively. The time differences were then used for epicenter placement relative to the ATL seismic station.

Table 6 gives the S-P time differences (Δ(S-P)) between the standard May 9, 1969 event and those found for six other events. Events which were cross-correlated were selected as typical events from different dates in

Table 5. List of Events and Phase Time Differences at the ATL Seismic Station

Date	Time (GMT) P at ATL[+]	S-P Seconds	Distance Kilometers[++]
2/13/74	06:56	21.50	191.5 ± 10
10/08/73	13:38	21.30	189.7 ± 10
4/26/71	09:04	21.44	190.9 ± 10
4/16/71	07:31	21.22	188.9 ± 10
5/18/69	10:56	21.66	192.9 ± 10
5/18/69	10:54	21.65	192.8 ± 10
5/09/69	12:14	21.47	191.2 ± 10
4/07/65	07:41	21.10	187.9 ± 10
4/06/65	21:19	19.36	172.4 ± 10
12/29/64	07:16	21.69	193.2 ± 10
12/28/64	17:33	21.83	194.4 ± 10
3/07/64	18:03	19.31	172.0 ± 10
10/07/63	06:02	21.04	187.4 ± 10

[+]P wave arrival at ATL to the nearest minute

[++]Accuracy is ± 10 km based on ± 0.1 sec error for phase arrival and ± 0.3 km/sec error in P wave velocity

Table 6. Numerical Results of Phase Cross-Correlation Study

Date	Cross-Correlation Coefficients		Δ(S-P)	D km
	P	S		
10/08/73	.47	.84	-1.1	- 7.15
4/16/71	.27	.58	+1.8	11.7
5/18/69	.69	.80	+0.2	1.3
4/07/65	.70	.77	-0.4	- 2.6
12/29/64	.31	.90	+0.2	1.3
3/07/64	.57	.66	+0.4	2.6

order to detect any differences in phase character and to observe migration of activity, if any.

Normalized cross-correlation coefficients reflect the agreement between the cross-correlated seismic traces. It is observed that S correlations are always better than P correlations which is in part due to trace amplitude. However, the October 8, 1973 and April 16, 1971 events show differences which are considerably larger than those of the other four events, as indicated by Δ(S-P). On examination of trace amplitude, it is found that these events exhibit smaller P phases with respect to other phases in the wave train. This is indicative of a difference in source mechanism or position from the other events. Values for Δ(S-P) for events prior to 1969 show less than a $\pm$ 0.5 second deviation from the May 9, 1969 epicenter which corresponds to differences of less than $\pm$ 3.5 km for the earlier events. The October 8, 1973 and April 16, 1971 events, however, show larger deviations which indicate variations of $\pm$ 7.2 and $\pm$ 11.7 km from the May 9, 1969 epicentral distance.

Epicenters for two events were calculated from data supplied by seismic stations at Oak Ridge, Tenn. (ORT), McMinnville, Tenn. (CPO), and Jenkinsville, South Carolina (JSC) as well as the existing ATL data. Epicenters were computed using an iterative, weighted, least-squares fit to a local travel-time curve (Appendix A). These two best-located events occurred on May 9, 1969 and on February 13, 1974. These events were located at 33.79°N, 82.58°W, and 33.62°N, 82.48°W, respectively with a precision of $\pm$ 10 km (Figure 12). The most recent event occurring (February 13, 1974) in the Clark Hill area was located in the southern reservoir

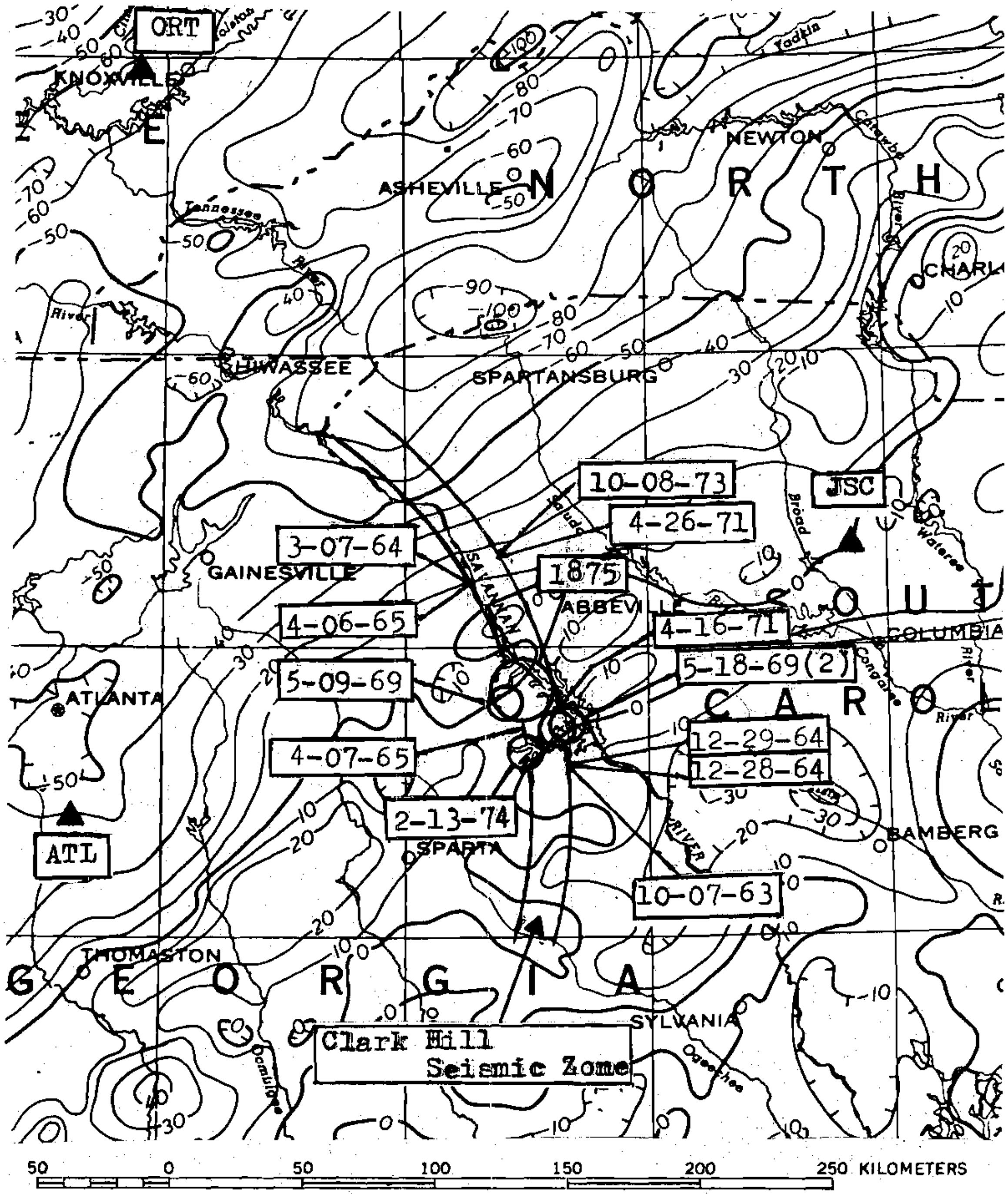


Figure 12. Epicenter Locations in the Reservoir Area from Southeast Seismic Data (Base Map; Woollard <u>et</u> <u>al</u>. 1964).

area and was the first event reported by JSC for the reservoir area since installation in November 1973. This event exhibits the same S-P at ATL as the May 9, 1969 event.

As seen from Table 6, those events which were compared to the May 9, 1969 event fall on arcs symmetrically disposed about the May 9, 1969 epicenter. These arcs pass in close proximity to the presumed location of the 1875 epicenter.

Displacement spectra for the events (Figure 13) were computed from the digitized time series and show corner frequencies at 1.5 to 2.0 hertz. Higher corner frequencies are usually observed for quarry explosions, whereas earthquakes are observed to produce low frequencies of this type.

The average local magnitude for the events examined is 3.2, and on the basis of the limited number of events recorded, the average return period for a magnitude 3.0 event appears to be on the order of 8 to 9 months.

An interesting feature of the Clark Hill events is that some (May 18, 1969, December 28, 1964) are double events or else they occur in rapid succession. Frequently, events are found within hours or at most a few days of each other. This may indicate that stress is being released along more than one fault segment, or that stress release takes place as a succession of events along a single fault.

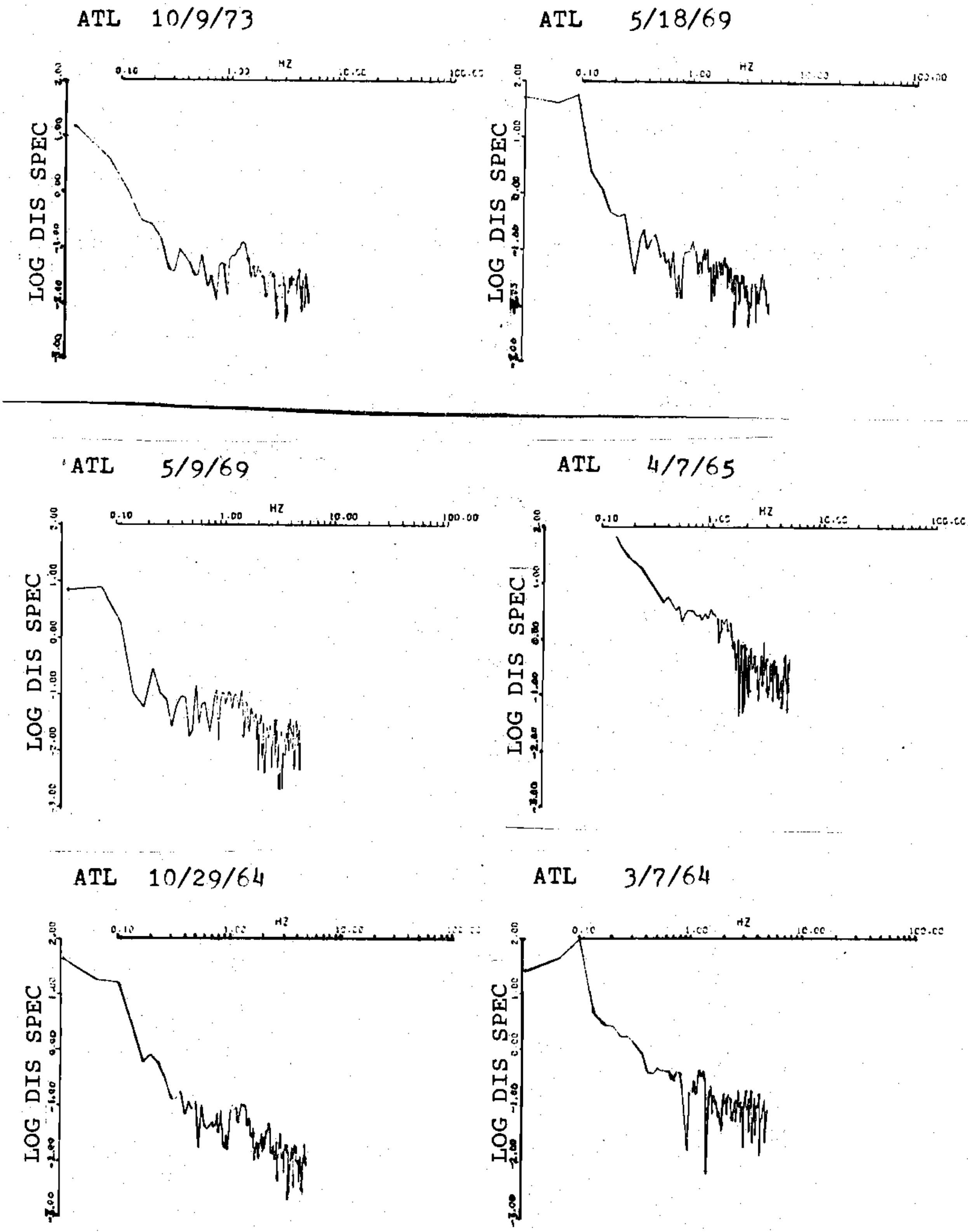


Figure 13. Displacement Spectra for Clark Hill Events.
(Spectra for P and S phases reveals a corner frequency near 2 hz.)

CHAPTER VI

MICROEARTHQUAKE SURVEYS

Seismic monitoring with smoked paper recorders began in September, 1973 and continued through April, 1974. Periodically, the instruments were relocated in the hope of recording events at each location and allowing location of a common epicentral zone. Table 7 lists the recording sites, the durations of operation, and the numbers of days of low noise recording. Along with the smoked paper units, a three component tape system was operated in the area (stations MSP and TPS). Figure 14 shows the locations of all stations occupied. On the basis of character and amplitude several events appear to be of natural origin (Table 8). Quarry activity has been ruled out since these events are characterized by distances which do not agree with distances to local quarries; occur at night or in the early morning hours when blasting operations are normally inoperative; and/or epicenters locate over bodies of water. These microearthquakes seem to satisfy a possible common epicentral zone in southern Lincoln County. Since single stations were used for most of the monitoring, these events cannot be uniquely located. Using the hypothesis of a possible common epicenter, a microearthquake seismograph array was designed to cover the Little River area.

Microearthquakes fall into two categories on the basis of character. The first category (Type I) exhibits small, but distinct P and S phases and comparatively large surface phases. The second category (Type II)

Table 7. Recording Stations

Station	Dates of Operation From	Dates of Operation To	Recording (Days)
DBR	9/13/73	10/31/74	26
ESP	11/12/73	12/07/73	10
CHR	11/12/73	11/30/73	5
FSH	12/06/73	12/13/73	6
BBD	12/06/73	12/13/73	6
TPS	12/06/73	12/13/73	2
LTV	12/13/73	12/30/73	10
CLY	12/31/73	1/04/74	5
NHC	12/31/73	1/04/74	5
MSP	12/31/73	1/04/74	2
AMT	2/19/74	4/15/74	8
		Total Low Noise Rcd.	85

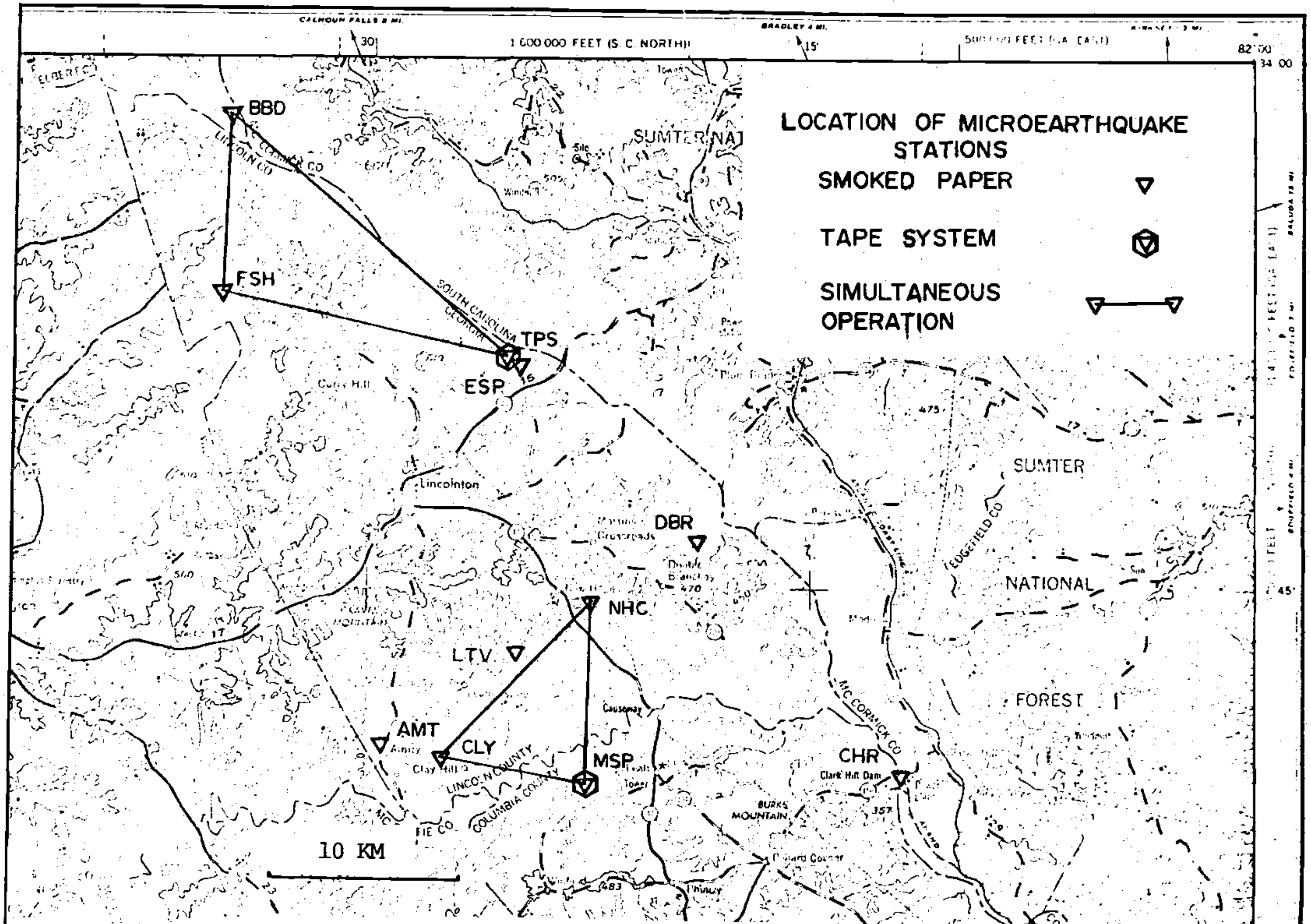


Figure 14. Locations of Microearthquake Stations Occupied.

Table 8. List of Clark Hill Microearthquakes

Date	Time (GMT)	Station	S-P (Sec)	Distance (Km)
9/22/73	01:57	DBR	1.80	14.42
10/12/73	11:11	DBR	2.73	21.86
10/13/73	11:02	DBR	0.79	6.35
10/16/73	13:20	DBR	1.96	15.69
10/16/73	13:41	DBR	1.96	15.69
10/16/73	15:34	DBR	1.96	15.69
11/16/73	12:48	DBR	1.63	13.05
1/03/74	01:30	ESP	1.77	14.20
1/04/74	18:30	CLY	0.53	4.20
1/04/74	18:30	NHC	1.24	9.90
1/04/74	18:30	MSP	0.4	3.20

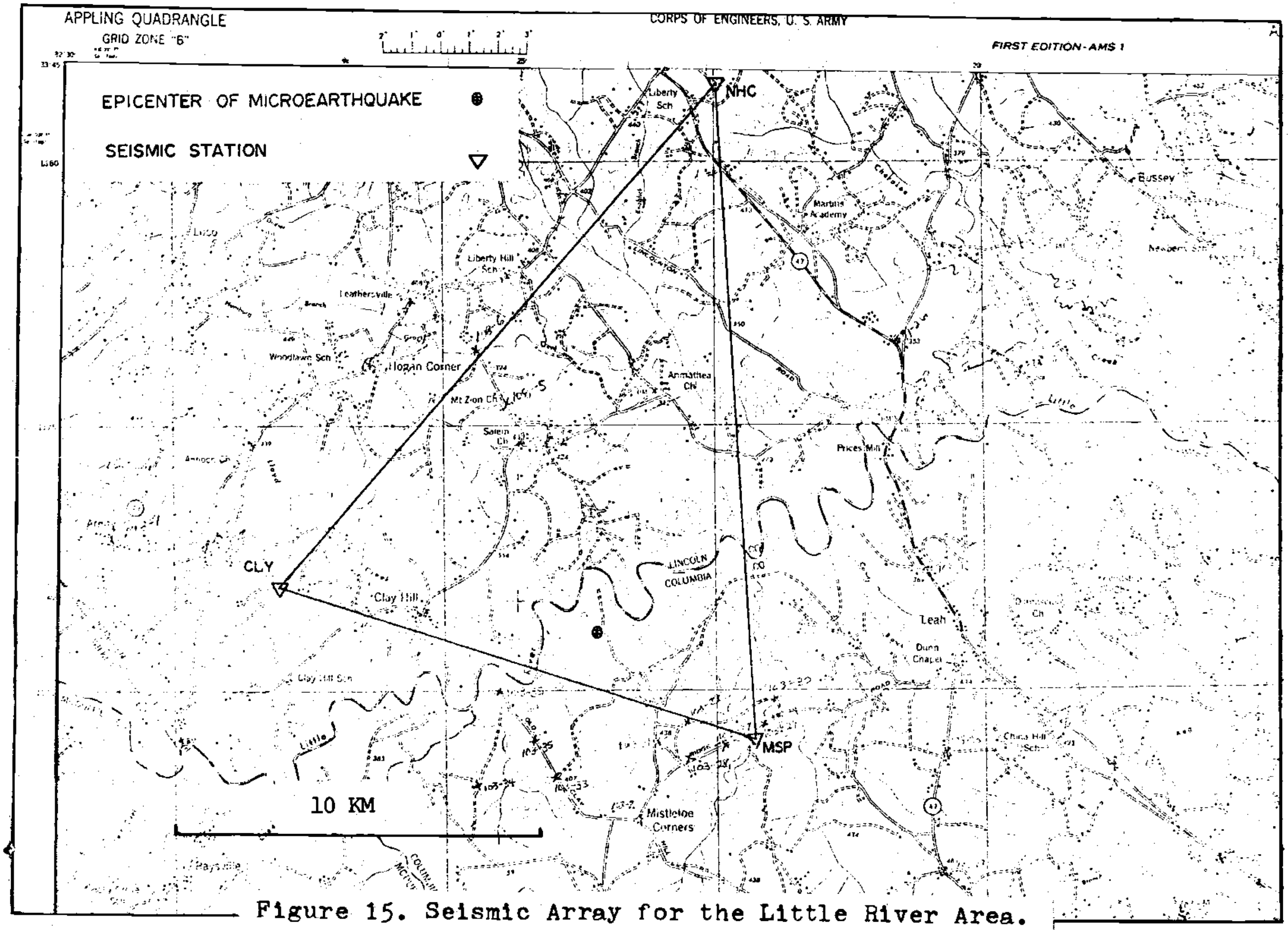
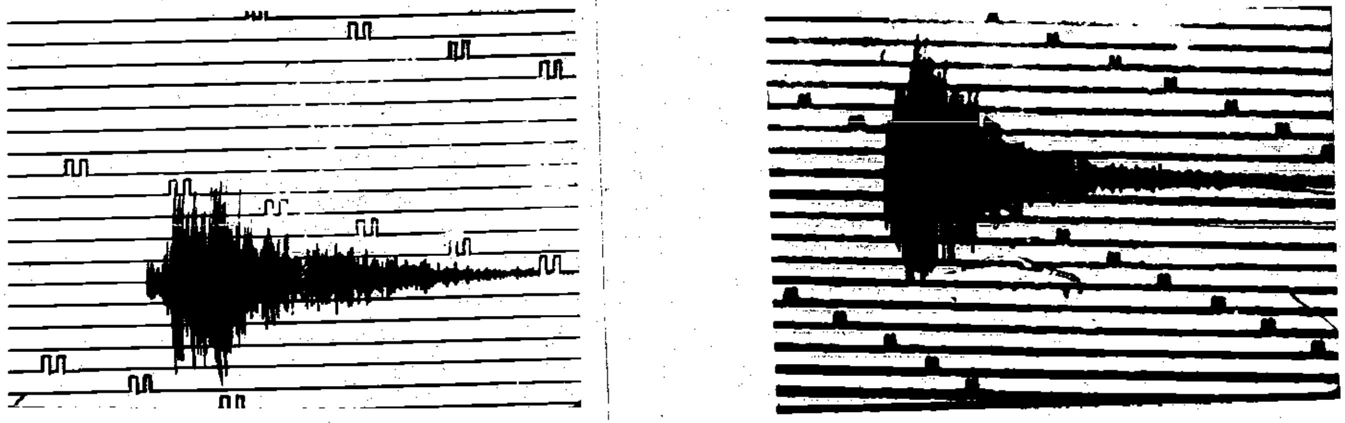


Figure 15. Seismic Array for the Little River Area.

exhibits larger P phases which often partially or wholly obscure the first arrivals of the S and surface waves. Type I events are exemplified by the September 22, 1973 (Figure 16) and the January 4, 1974 (Figure 17) events. Type II events are exemplified by the October 12, 1973 microearthquake (Figure 16).

Stations in the seismic array had a capability of recording seismic events equivalent to those produced by approximately 1000 pounds of explosive at a distance of 50 kilometers. During the operation of the array in the Little River area, a microearthquake was recorded by three stations on January 4, 1974. The epicenter of this event was computed (Appendix A) as $33^{\circ}39.63'$ and $82^{\circ}24.12'$ with a maximum probable error of $\pm$ 0.1 km. This location falls over the Little River arm of the Clark Hill Reservoir (Figure 15). The event was recorded on magnetic tape, which allowed more detailed examination of the phases than is possible with the smoked paper records (Figures 17, 18). The P and S phases are distinct, and the event occurred only 3.2 km from recording station MSP. A near surface focus is indicated for the event.

Displacement spectra were determined for the P and S phases of the microearthquake and, for comparison, so were those of a local quarry explosion at a distance of 40 kilometers (Figure 19). Examination of the displacement spectra indicates that the corner frequency for the microearthquake occurs between 10 and 20 hertz. The S wave microearthquake spectra exhibits a corner in the 10 to 15 hertz range. The P wave microearthquake spectra is indeterminant. Spectra for the quarry blast do not exhibit a sharp corner frequency and can be explained by attenuation of the higher frequencies with distance.



September 22,1973 GMT 4:57

October 12,1973 GMT 11:11

Figure 16. Records of the Type I and Type II Microearthquakes.

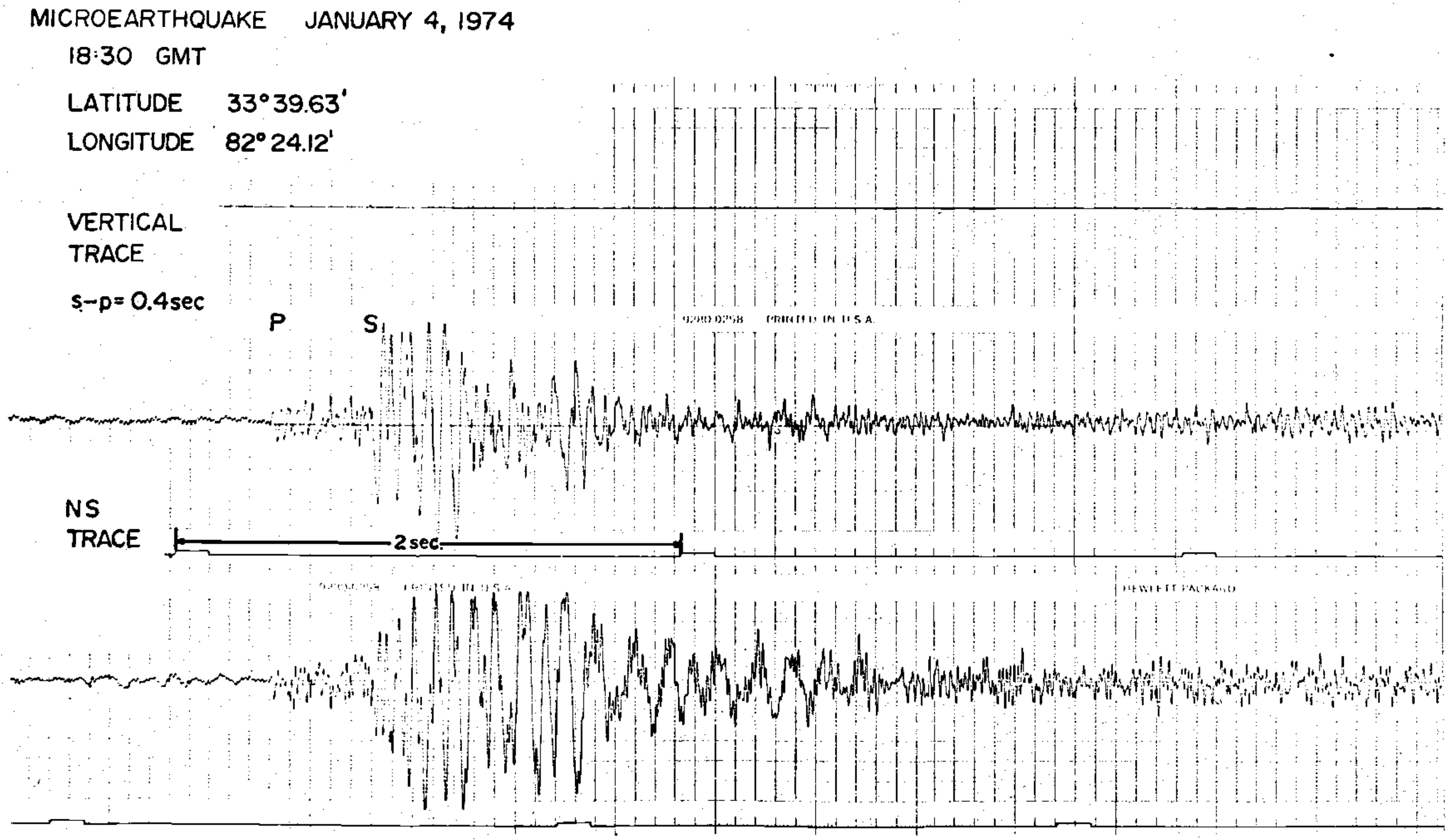


Figure 17. Strip Chart Record of the January 4,1974 Microearthquake.

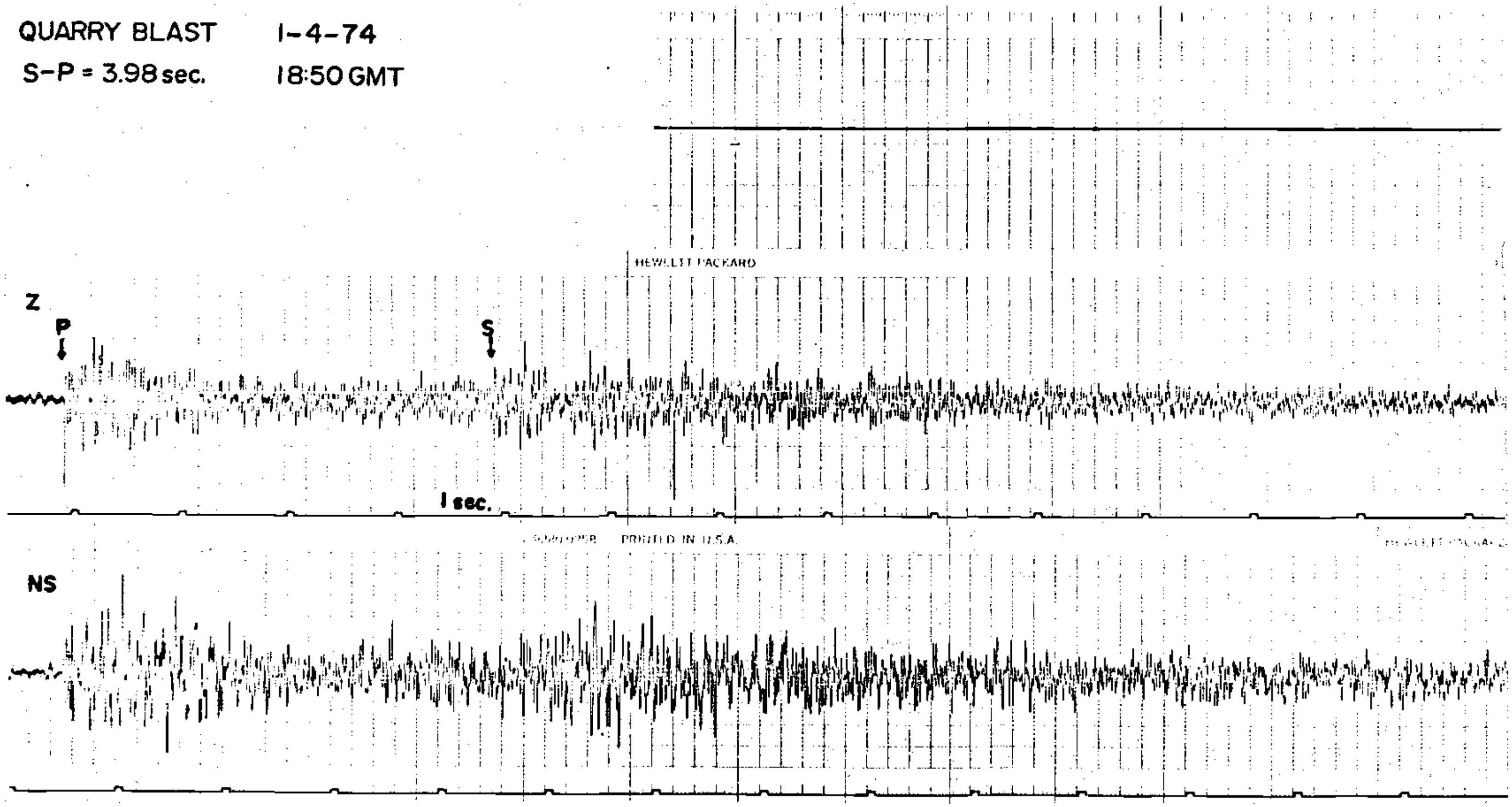


Figure 18. Strip Chart Record for a Local Quarry Blast.

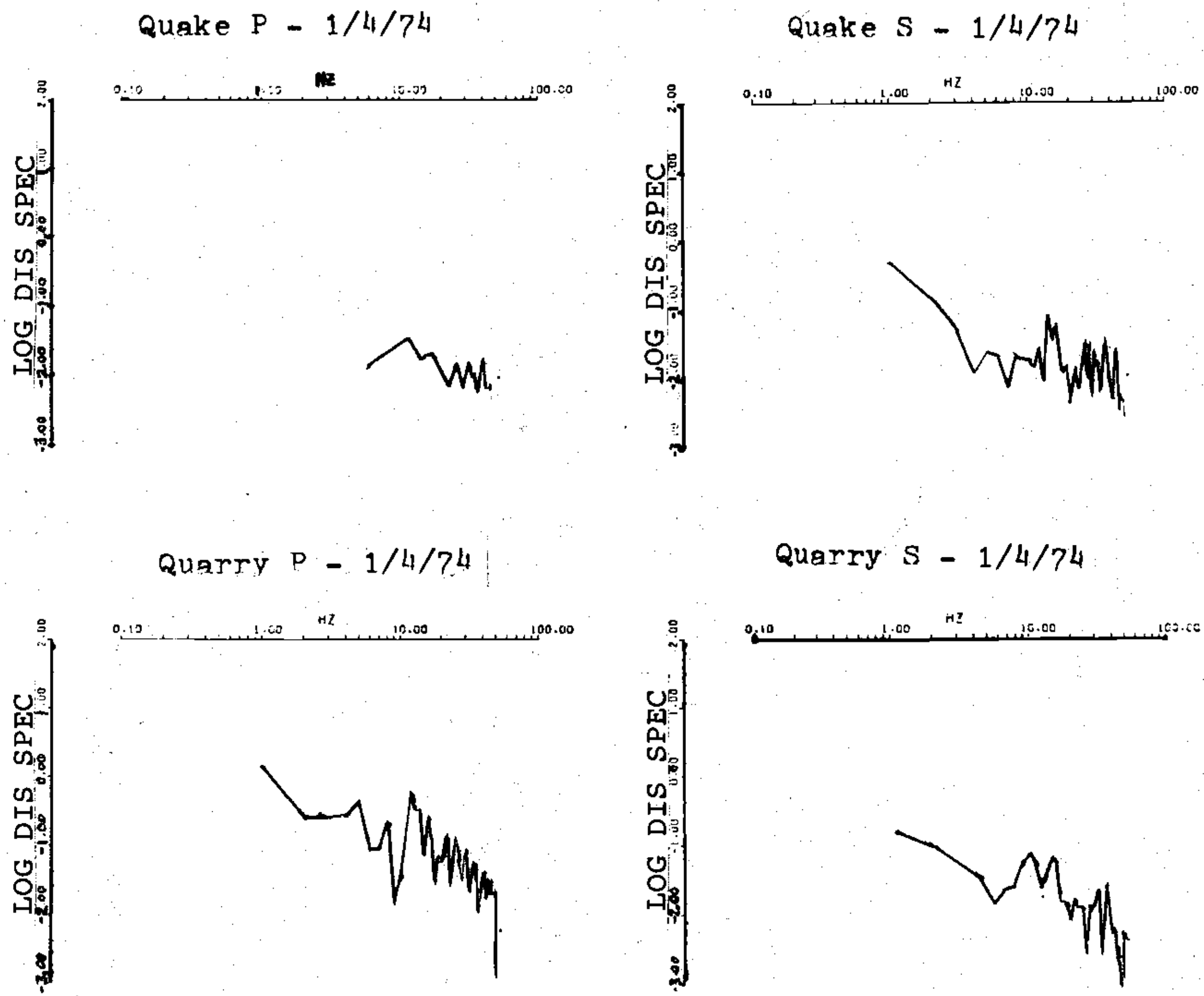


Figure 19. Displacement Spectra for Microearthquake and Quarry Blast.

CHAPTER VII

TECTONIC IMPLICATIONS FROM GEOPHYSICAL AND GEOLOGICAL DATA

Several interesting conclusions may be drawn from the examination of the geophysical data and the geological evidence presented in the preceding sections. In light of the current seismic activity exhibited in the reservoir area and of the historic event of 1875, it is reasonable to conclude that the east-central Georgia Piedmont is undergoing a natural low-level stress release which is manifested as microearthquake activity. The events which have occurred in the past 10 years are of local magnitude less than 3.6. Residents of the sparsely populated area are apparently unaware of the earthquakes, and have most likely attributed any felt events to the local quarry activity.

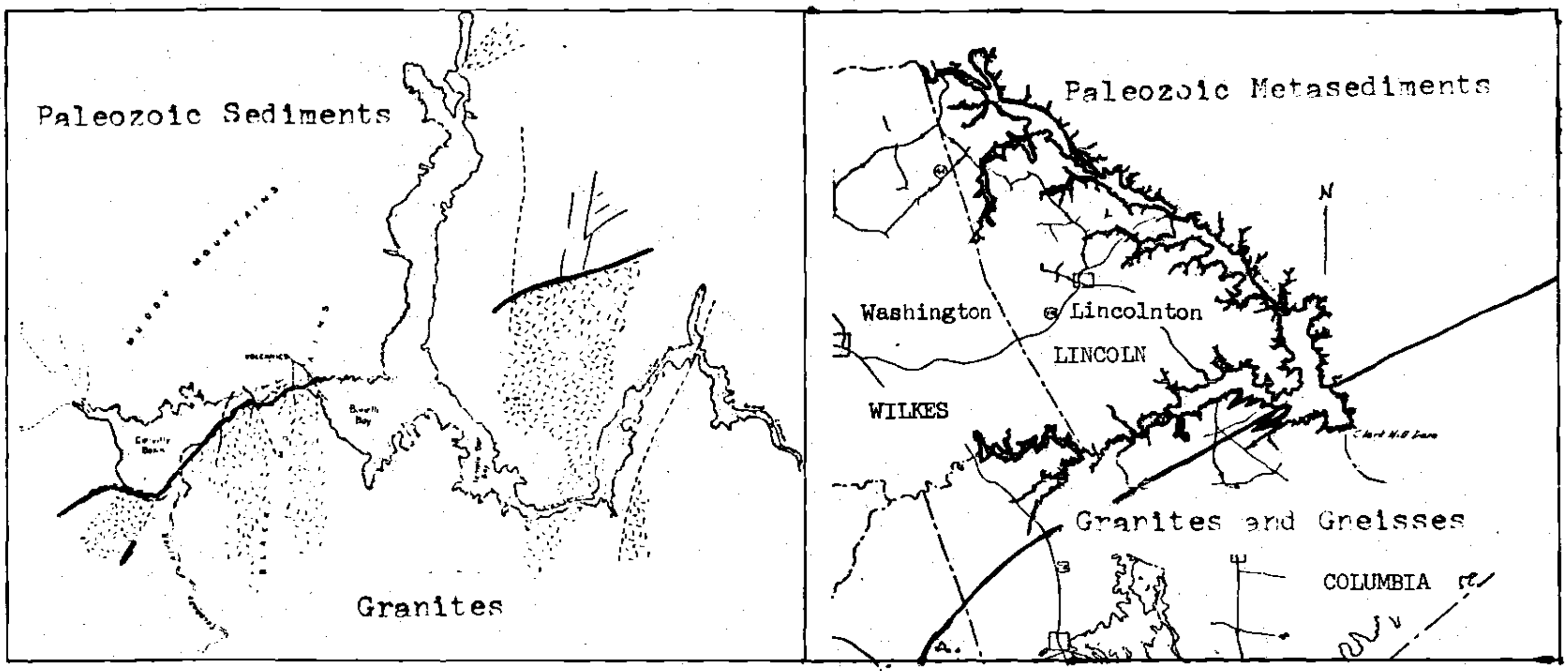
Relocation of the May 9, 1969 epicenter to the west of Lincolnton, Georgia and location of the February 13, 1974 epicenter in the Little River area indicate that seismic activity is associated with central and southern Lincoln County. Results of the phase cross-correlation indicate the possibility that other epicenters may have been within this area, since only small deviations are observed from the May 9, 1969 epicentral distance, based on the correlation functions.

The microearthquake of January 4, 1974, at 18:30 GMT is the first natural seismic event occurring in Georgia to be located to a precision of ± 0.1 km. To date it is also the only microearthquake with an epicenter in Georgia to be recorded by a three station field recording array. The epicenter of this event is located along the strike of an apparent shear which extends NW-SE and offsets a prominent seven milligal Bouguer anomaly in the southern reservoir area. The epicenter also lies near the northeast trending shear zone which extends through the Little River area. Therefore two structural trends are present along which the observed seismic activity may possibly occur. Northwest trending faults in the area have been shown to be active at least as recent as late Cretaceous (O'Connor et al., 1974). These faults are the most likely candidates for the source of the observed seismic activity. The possibility of seismic activity along the NE trending shear zone, however, cannot be ruled out at this time. Further recording will be required in order to obtain additional precisely located microearthquakes in central and southern Lincoln County and to develop focal plane solutions for these events.

The 7.9 milligal ridge on the Bouguer gravity map for the reservoir area is attributed to a serpentinite material which was most likely a peridotite before metamorphism. This material lies in contact with the highly deformed button schist unit which comprises a prominent shear zone in the area, and it is faulted down against other Little River series members. Northeast trending features such as this have been described in connection with another study involving seismicity (McKee, 1973) in the Southeast. The metadacite unit is the source of a 6.5 milligal NE trending ridge of positive Bouguer anomalies which are caused by a structure of about 6.4 km width. Granite bodies of intrusive episode C are observed to produce large negative gravity anomalies on the order of - 16 milligals which indicate substantial vertical and lateral extent of these lithologic units, as well as negative density contrasts.

Due to the presence of the Clark Hill Reservoir, the influence of reservoir loading on seismicity merits consideration. Carder (1945) examined seismic activity at Lake Mead and found that earthquake swarms developed as the reservoir was filled. At Lake Mead seismic activity developed along a zone of weakness when loading of the sedimentary sequences produced failure of the rock material along ancient fracture zones. Geological conditions existing at Clark Hill are similar. There, the dam has been constructed at the contact of brittle crystalline gneisses with the low grade metamorphosed sediments of the Carolina slate belt (Figure 20). Other studies that have associated seismicity with reservoirs or lakes are those of Gupta et al. (1972 a, b) and Sbar et al. (1970).

The Clark Hill reservoir was completed in 1954 as a U.S. Army Corps of Engineers project. The lake storage capacity is 2.5 million acre-feet at full power pool which constitutes a load of 3.4 billion tons over an area of 70,000 acres. An additional 390,000 acre feet of flood storage capacity provides a surplus load of 530 million tons which covers an additional 8,500 acres at the maximum design pool elevation. Maximum variation in pool elevation is 34 feet at the Clark Hill dam, which amounts to a load variation of 95 million tons or 2.8% of the water weight and a pressure variation of 1.03 atmospheres at the soil-water interface. If reservoir loading has an effect at Clark Hill, a relationship should exist between water level and frequency of occurrence and magnitude of the microearthquakes. Examination of reservoir records for the years 1968 through 1974 (Figure 21) reveals only two occasions where a change in level of over 2 meters corresponds to the occurrence of a microearthquake within three to four weeks after such a change. Peak reservoir levels were



Lower Lake Mead Region

after Carder, 1945

Clark Hill Reservoir Area

Figure 20. Similarity of Geologic Conditions at Lake Mead and the Clark Hill Reservoir.

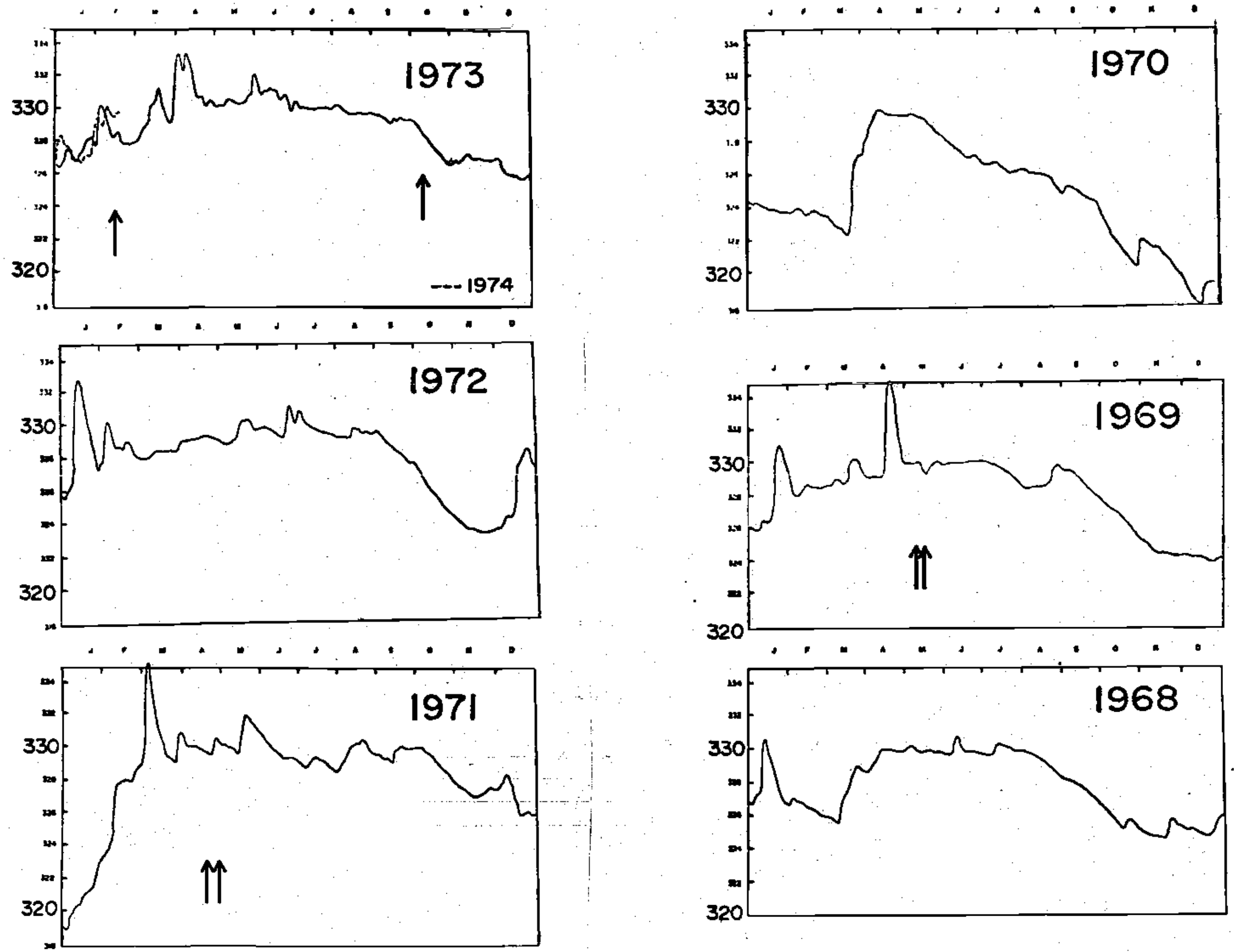


Figure 21. Clark Hill Reservoir Lake Levels for 1968 - 1974.
(Arrows represent times of earthquake occurrences)

reached during 1969 and 1971, and the reservoir was rapidly returned to normal pool elevation. These events were followed by the microearthquake swarm during the summer of 1969 and by two microearthquakes in April 1971 (Figure 21). Many other changes in reservoir level have occurred, as evidenced by the graphs in Figure 21; however, events of sufficient magnitude to be registered at ATL have not been identified. The graph for 1973-1974 shows no correlation with the microearthquakes recorded during those years.

Past studies in which it has been possible to relate seismic activity and loading have been associated with lakes deeper than 100 meters and with loading of an area over a period of months. The Clark Hill reservoir has a maximum depth of only about 40 meters and its loading curves show no similarity to those observed for reservoirs indicating loading effects (Carder, 1945). This suggests that the reservoir itself is not responsible for production of seismic activity through loading, but it does not rule out the possibility that large lake level fluctuations act as a catalyst when stress conditions reach levels suitable for the production of microearthquakes. More events showing relationships similar to the two existing cases will have to be observed before this possibility can be evaluated.

The occurrence of a historic earthquake of moderate intensity in the Clark Hill area long before the construction of the Clark Hill dam and the filling of the reservoir indicates that the east-central Georgia Piedmont has previously accumulated tectonic stresses sufficient to cause earthquake activity and that the phenomena responsible for these stresses are possibly active today and are the cause of the observed seismic activity.

CHAPTER VIII

RECOMMENDATIONS

Continued local monitoring of the low level seismic activity in the Clark Hill area is recommended since this is the first known occurrence of such a zone of seismic activity in Georgia, and it indicates stress conditions which have been overlooked in the past. The nature and magnitude of these seismic events might be reasonably well determined by a program of local seismic monitoring; however, this program should last not less than two years, since activity at this locality, as elsewhere in the Southeastern United States, is infrequent. However, due to the proximity of population centers and existing, or planned, construction in the area, this infrequency does not diminish the importance of a full assessment of the seismicity.

Continued acquisition of gravity data should provide a good method of detecting fault systems within the area, particularly, where high density units are present. Reducing the grid spacing to 0.5 km would provide better resolution of the major units, as well as aid in the identification of smaller structures. Gravity maps can also be used to identify areas where detailed field mapping would be most productive. Detailed geologic mapping to positively identify faults and determine the stratigraphic succession of the crystalline rocks, as well as to provide samples for density determinations, would also be helpful.

Aeroradiometry and aeromagnetic surveys with flight line spacings of one kilometer or less have been shown to be useful in the determination of structure and the identification of geologic units; maps of this nature compiled for the Clark Hill area would be instructive and useful. Currently, no such coverage is available for this area, but the U.S. Geological Survey North-Central Georgia magnetic map reveals trends which may continue into east-central Georgia.

In-situ stress measurements on the rock materials within the area might also provide indications of the stress conditions which are producing the seismic activity.

APPENDICES

APPENDIX A

SEISMIC DATA COLLECTION AND ANALYSIS

Data Preparation

Seismic data obtained from the ATL seismograms were digitized for spectral and cross-correlation studies. The records of the events were first contact printed onto celluloid and projected on a microfilm reader (magnification 14.5X) for digitizing. Digitizing was performed by measuring the times and heights of the peaks, troughs, and inflection points of the time series traces. Data points between the measured points were then interpolated using a cosine function, and corrections were applied for the calibration pulse prior to digitizing to insure 0.1 second precision. The time series representations with data interpolated at equal intervals were transformed into the spectral domain using a Fourier transform method (see program SPECLE). Instrument response was corrected for in the frequency domain and spectra computed for six events.

Equation for Cross-correlation Computations

Normalized cross-correlation coefficients were computed from seismic traces digitized at equal time intervals. The seismic traces were sequentially overlapped at 0.1 second intervals (the digitizing interval) and their cross-correlation coefficients computed from the expression (Davis, 1973, p. 234)

$$r_m = \frac{n^* \Sigma Y_1 Y_2 - \Sigma Y_1 \Sigma Y_2}{[n^* \Sigma Y_1^2 - (\Sigma Y_1)^2][n^* \Sigma Y_2^2 - (\Sigma Y_2)^2]}$$

where m is the match position, r_m the cross-correlation coefficient, n^* the number of overlapped positions, and Y_1 and Y_2 the two data sequences to be compared.

Location Programs

Epicenter location techniques were of two types. The first technique applied was to generate a grid about the epicentral area of standard deviations for theoretical and observed differences in times of body phases at each grid point (see program ERROR GRID). Reliable locations may be obtained in this manner where proper time-distance relations are assumed and data are of uniform precision. The second epicenter location technique (see program DO-ALL) is an iterative, weighted, least-squares computation (Wiggins, 1972) designed to compute the epicenter with the minimum weighted error. The weights govern the influence of the data and parameters computed so that poor data can be suppressed or poorly defined parameters eliminated. Listings of computer programs used for seismic data analysis are incorporated in this appendix.

Microearthquakes and quarry blasts were recorded on Sprengnether smoked paper seismograph systems designed for a flat response between 5 and 30 hertz. Hall-Sears HS 10-1A geophones of both 123,000 Ω and 350 Ω impedance were used for recording. Voltage gains for systems were varied between 3600 and 12,500 depending on recording site and time of day.

PRINTOUT OF XQUAKE

```
C*****PROGRAM XQUAKE FOR CROSSCORRELATION OF SEISMIC WAVES
      DIMENSION T(1000),H(1000),F(2000),F1(2000)
      K=1
   05 READ(5,101) N,NDT,DT,TI,TCAL,HCAL,LAB
  101 FORMAT(2I5,4F10.5,4A6)
      WRITE(6,103) N,NDT,DT,TI,TCAL,HCAL,LAB
  103 FORMAT(1H1,I5,41H PAIRS OF POINTS ARE TO BE INTEPOLATED AT ,I5
     1,7H POINTS,F10.2,14H SECONDS APART,//13H BEGINNING AT, F10.3/
     215H TCAL UNITS/SEC,1F10.3,15H HCAL UNITS/MM,1F10.3//4A6)
      TTIME=DT*NDT
      READ(5,102) (H(I),T(I),I=1,N)
  102 FORMAT(10F7.0)
      WRITE(6,104) (H(I),T(I),I=1,N)
  104 FORMAT(1X,10F10.3)
      DO 20 I=1,N
   21 H(I)=H(I)*HCAL
   20 T(I)=T(I)/TCAL
      WRITE(6,180)
  180 FORMAT(1H1,'VALUES OF H AND T CORRECTED TO MM. AND SEC.'/)
      WRITE(6,105)(H(I),T(I),I=1,N)
  105 FORMAT(1X,10F10.3)
      CALL DIGI(H,T,N,TI,NDT,DT,F)
      IF (K.NE.1) GO TO 40
      TTIME1=TTIME
      NDT1=NDT
      DO 41 I=1,NDT
      F1(I)=F(I)
      F(I)=0
      T(I)=0
   41 H(I)=0
      K=K+1
      GO TO 05
   40 CONTINUE
      CALL CRSCR(F1,NDT1,F,NDT)
      WRITE(6,106) DT
  106 FORMAT(1H0,'TIME INTERVAL=',F10.3)
      STOP
      END
C
C
      SUBROUTINE CRSCR (XIN1,NIN1,XIN2,NIN2)
C*****PROGRAM FOR ROUTINE CROSSCORRELATION STUDY OF SEISMIC WAVES.
C     MODIFIED FROM S5.9,DAVIS,J.C.,STATSTICS AND DATA ANAYSIS IN GEOLOGY.
C     PROGRAM PERFORMS ROUTINE CROSSCORRELATION OF TWO DATA SEQUENCES.
C     XIN1 CONTAINS THE FIRST DATA SEQUENCE OF NIN1 ELEMENTS.
C     XIN2 IS THE SECOND DATA SEQUENCE OF LENGTH NIN 2.
C     THE CORRELATION COEFFICIENTS CALCULATED AT EACH MATCH POSITION ARE
C     STORED IN ARRAY XOVT.  THE NUMBER OF COPRELATION COEFFICIENTS IN
C     XOUT IS NOT=NIN1+NIN2-5
C     IB1=FIRST TERM OF XIN1 IN THE OVERLAPPED SEGMENT
C     IE1=LAST TERM OF XIN1 IN THE OVERLAPPED SEGMENT
C     IB2=FIRST TERM OF XIN2 IN THE OVERLAPPED SEGMENT
C     IE2=LAST TERM OF XIN2 IN THE OVERLAPPED SEGMENT
C     LEN1=NUMBER OF TERMS OF XIN1 IN THE OVER LAPPED SEGMENT
```

PRINTOUT OF XQUAKE (Cont.)

```
C      LEN2=NUMBER OF TERMS OF XIN2 IN THE OVER LAPPED SEGMENT
C
C      SUBROUTINES REQUIRED: TSPLOT,DIGI
C*****MAXIMUM LENGTH OF EACH DATA SEQUENCE IS 500 ELEMENTS.
C*****************************************************************************
C      READ IN THE TWO DATA SEQUENCES TO BE CROSSCORRELATED, PRINT THEM OUT
C               AND PLOT THEM ON THE LINE PRINTER.
       DIMENSION XIN1(500),XIN2(500),XOUT(1000)
    10 WRITE(6,2007) XIN1
       WRITE(6,2002)
       WRITE(6,2004)
    11 WRITE(6,2007) XIN2
       WRITE(6,2003)
       CALL TSPLOT(XIN2,NIN2,2)
       WRITE(6,2005)
       WRITE(6,2000)
       NOT=NIN1+NIN2-5
       IB1=1
       IE1=3
       IB2=NIN2-2
       IE2=NIN2
       LEN1=3
       DO 100 I=1,NOT
       SX=0.0
       SY=0.0
       SXY=0.0
       SXX=0.0
       SYY=0.0
       DO 101 J=1,LEN1
       J1=IB1+J-1
       J2=IB2+J-1
       SX=SX+XIN1(J1)
       SY=SY+XIN2(J2)
       SXY=SXY+XIN1(J1)*XIN2(J2)
       SXX=SXX+XIN1(J1)**2
       SYY=SYY+XIN2(J2)**2
   101 CONTINUE
       AN=LEN1
       R=(AN*SXY-SX*SY)/SQRT((AN*SXX-SX*SX)*(AN*SYY-SY*SY))
       T=R*SQRT((AN-2.0)/(1.0-R*R))
       XOUT(I)=R
       WRITE(6,2001)I,IB1,IE1,IB2,IE2,LEN1,R,T
       IE1=IE1+1
       IF (IE1-NIN1) 2,2,1
     1 IB1=IB1+1
       IE1=NIN1
     2 IB2=IB2-1
       IF (IB2) 3,3,4
     3 IB2=1
       IE2=IE2-1
     4 LEN1=IE1-IB1+1
       LEN2=IE2-IB2+1
       IF (LEN1-LEN2) 5,100,6
     5 IB1=1
       IE2=IE2-1
       GO TO 4
     6 IB1=IB1+1
```

PRINTOUT OF XQUAKE (Cont.)

```
      IE2=NIN2
      GO TO 4
  100 CONTINUE
      CALL TSPLOT (XOUT,NOT,1)
      WRITE(6,2006)
      CALL EXIT
 2000 FORMAT(1H1,14X,'TERMS WHICH ARE MATCHED',7X,'NUMBER'/
     14X,'MATCH',8X,'FIRST',9X,'SECOND',6X,'OF TERMS',
     23X,'CORRELATION',7X,'I'/3X,'POSITION',4X,'DATA SET',6X,
     32X,'DATA SET',6X,'MATCHED',2X,'COEFFICIENT',5X,'VALUE'/)
 2001 FORMAT(1X,6I8,2F14.6)
 2002 FORMAT(/'FIRST DATA INPUT SEQUENCE-XIN1')
 2003 FORMAT(/'SECOND DATA INPUT SEQUENCE-XIN2')
 2004 FORMAT(/'PLOT OF XIN1')
 2005 FORMAT(/'PLOT OF XIN2')
 2006 FORMAT(/'PLOT OF CROSSCORRELATION COEFFICIENTS')
 2007 FORMAT(1H0,8F10.3)
      RETURN
      END
C
C
      SUBROUTINE TSPLOT (X,N,ITYPE)
C     PROGRAM TO PLOT 1-DIMENSIONAL LINE DATA
C     X IS THE ONE DIMENSIONAL ARRAY TO BE PLOTTED.
C     N IS THE NUMBER OF ELEMENTS IN X THAT ARE TO BE PLOTTED.
C
C     IF ITYPE=1, THE DATA WILL HAVE RANGE FROM -1 TO 1
C     IF ITYPE=2, ANY DATA MAY BE PLOTTED
C     IF ITYPE=3, LOG10 OF THE X ARRAY WILL BE PLOTTED.
C     THE ORIGINAL ARRAY WILL NOT BE DESTROYED
C*****************************************************************************
      DIMENSION X(1),IOUT(61),XX(13)
      DATA II,ISTAR,IBLNK/'I','*',' '/
      IF (ITYPE.NE.1) GO TO 11
      XMIN=-1.0
      XMAX=1.0
      GO TO 12
   11 XMIN=X(1)
      XMAX=XMIN
      DO 100 I=1,N
      IF (X(I).LT.XMIN) XMIN=X(I)
      IF (X(I).GT.XMAX) XMAX=X(I)
  100 CONTINUE
      IF (ITYPE.NE.3) GO TO 12
      XMIN=ALOG10(XMIN)
      XMAX=ALOG10(XMAX)
   12 DX=XMAX-XMIN
      XXX=XMIN
      DO 101 I=1,13
      XX(I)=XXX
      IF (ITYPE.EQ.3) XX(I)=10.0**XXX
      XXX=XXX+DX/12.0
  101 CONTINUE
      WRITE(6,2004)
      WRITE(6,2000)(XX(I),I=2,12,2)
      WRITE(6,2001)(XX(I),I=1,13,2)
      WRITE(6,2002)
```

PRINTOUT OF XQUAKE (Concluded)

```
      DO 102 I=1,N
      DO 103 J=1,61
      IOUT(J)=IBLNK
  103 CONTINUE
      DO 104 J=1,61,10
      IOUT(J)=II
  104 CONTINUE
      XXX=X(I)
      IF (ITYPE.EQ.3) XXX=ALOG10(XXX)
      IX=IFIX((XXX-XMIN)*60.0/DX)+1
      IOUT(IX)=ISTAR
      WRITE(6,2003) X(I),IOUT
  102 CONTINUE
      WRITE(6,2002)
      WRITE(6,2001)(XX(I),I=1,13,2)
      WRITE(6,2000)(XX(I),I=2,12,2)
      RETURN
 2000 FORMAT(11X,6F10.4)
 2001 FORMAT(6X,7F10.4)
 2002 FORMAT(11X,'+',12('----+'))
 2003 FORMAT(1X,F10.4,61A1)
 2004 FORMAT(1H1)
      END
C
C
      SUBROUTINE DIGI (H,T,N,TI,NDT,DT,F)
      DIMENSION H(I), T(I), F(NDT)
      PI = 3.1415926536
      I = 0
      DO 20  J = 1,NDT
      TIME = TI + (J-1) * DT
   22 IF (T(I+1).GT.TIME) GO TO 20
      I = I+1
      GO TO 22
   20 F(J) = (H(I) + H(I+1))*0.5  + (H(I)-H(I+1))*0.5*COS(PI*(TIME-T(I)
     1)/(T(I+1)-T(I)))
      RETURN
      END
```

PRINTOUT OF ERROR GRID

```
C***** FIVE STEP PROCEDURE FOR EARTHQUAKE LOCATION (USING 3 STATIONS)
C      CHANGE THE STATION LOCATIONS CARD (DATA SLAT)
C      TO INCLUDE STATIONS USED
C      ENTER APPROPRIATE TRAVEL-TIME FUNCTIONS (TP-TS)
C      PUNCH HEAD CARD WITH GRID PARAMETERS
C      PUNCH DATA IN P & S PAIRS-#2 FOR P-#5 FOR S
C      BLANK CARD AT END OF DATA
C*************************************************************************
      COMMON IPH(20),Q(20),SI(20),ID(20)
      REAL LONG1,LONG2,LAT1,LAT2
      N=1
      READ(5,101)(EZ,ELA,ELO,XINCA,XINCO,LONG1,LONG2,LAT1,LAT2,NLAT,
     2NLONG)
  101 FORMAT(3F7.4,2F7.6,4F7.4,2I7)
      WRITE(6,101)EZ,ELA,ELO,XINCA,XINCO,LONG1,LONG2,LAT1,LAT2,NLAT,
     2NLONG
    4 READ(5,102) IPH(N),Q(N),SI(N),ID(N),LAB
  102 FORMAT(2X,I1,2(2X,F7.3),2X,I1,A6)
      IF (IPH(N).EQ.0) GO TO 5
      WRITE(6,202) IPH(N),Q(N),SI(N),ID(N),LAB
  202 FORMAT(1H ,'DATA INPUT',9X,I1,2(2X,F7.3),9X,I1,A6)
      N=N+1
      GO TO 4
    5 CONTINUE
      N=N-1
      WRITE(6,203)N
  203 FORMAT(1H0,'NUMBER OF PHASES USED IN THIS LOCATION IS',I2)
    6 CALL ERROR(EZ,N,ELA,ELO,XINCA,XINCO,LONG1,LONG2,LAT1,LAT2,
     2NLAT,NLONG)
      STOP
      END
C
C
C  SUBROUTINE ERROR FOR LOCATION OF EPICENTERS, VERSION 4/74
      SUBROUTINE ERROR(EZ,N,ELA,ELO,XINCA,XINCO,LONG1,LONG2,LAT1,LAT2,
     2NLAT,NLONG)
C     EZ-DEPTH OF FOCUS,N-NUMBER OF PHASES ENTERED AS P AND S PAIRS
C     ELA,ELO-N.W.CORNER OF GRID,XINCA,XINCO-SCALE FACTOR IN DEGREES/GRID
C     LONG1,LONG2,LAT1,LAT2-RANGE OF ERROR GRID IN DEGREES.
C
      DIMENSION SLAT(3),SLONG(3),ER(500)
      COMMON IPH(20),Q(20),SI(20),ID(20)
      NCON=NLONG+1
      WRITE(6,204)
  204 FORMAT(1H0,'STATION LATIDUDES AND LONGITUDES')
      DATA SLAT/33.433,34.2798,35.595/,SLONG/84.338,81.2598,85.571/
      WRITE(6,203) SLAT,SLONG
  203 FORMAT(1H0,10F10.4)
      I=0
      SUELP=0
      SUELS=0
      WRITE(6,91)
   91 FORMAT(1H1,29X,'EARTHQUAKE LOCATION ERROR GRID')
      WRITE(6,92) LONG1,LONG2
```

PRINTOUT OF ERROR GRID (Cont.)

```
   92 FORMAT(/23X,'LONGITUDE COORDINATES IN DEGREES',2F8.4)
      WRITE(6,93) LAT1,LAT2
   93 FORMAT(23X,'LATITUDE COORDINATES IN DEGREES',2F8.4)
      WRITE(6,94) EZ
   94 FORMAT(23X,'DEPTH OF FOCUS = ',F6.3)
C*****COMPUTE ERROR GRID
C  DETERMINATION OF X,Y DISTANCE FROM CORNER (ELA,ELO)
      DO 10 LA=0,NLAT
      I=0
      ELAT=ELA-LA*XINCA
      DO 10 LO=0,NLONG
      ELONG=ELO-LO*XINCO
C  CONVERSION OF X,Y DISTANCE TO RESULTANT IN KM.
      DO 101 NN=1,N
      II=ID(NN)
  405 FORMAT(4F12.4)
      CALL CXY(ELAT,ELONG,SLAT(II),SLONG(II),A,B)
      D=(A**2)+(B**2)
      R=SQRT(D)
C  TEST FOR P OR S CALCULATION
      IF (IPH(NN).EQ.5) GO TO 303
C  TRAVEL-TIME FOR P-WAVE (TT CURVE)
      TP=.8+R/6.5
      DELP=Q(NN)-TP
      GO TO 101
C  TRAVEL-TIME FOR S-WAVE (TT CURVE)
  303 TS=2.7+R/3.7
      DELS=Q(NN)-TS
C  SQUARE OF DIFFERENCE (OBS.-THEO.TT)
      SDELP=SDELP+DELP**2
      SDELS=SDELS+DELS**2
  101 CONTINUE
C  COMPUTE THE MEAN SQUARE DEVIATION
  304 SUM=(SDELS+SDELP)/N
      SDELP=0
      SDELS=0
C  COMPUTE ERROR FN. AND TEST FOR PRINT
      I=I+1
      ER(I)=SQRT(SUM)
      IF (I.EQ.NCON) GO TO 305
      GO TO 10
C  PRINT OUT ERROR GRID
  305 WRITE(6,90)(ER(II),II=1,NCON)
   90 FORMAT(1X,20F6.3)
   10 CONTINUE
      RETURN
      END
C
C
      SUBROUTINE CXY(YO,XO,ALAT,ALONG,X,Y)
C*****(YO,XO) IS ORIGIN IN DEGREES<500KMFROM DATA FOR < .1KM ERROR
C*****(ALAT,ALONG) LATITUDE AND LONGITUDE OF DATA POINTS
C*****FROM RICHTER-ELEM SEIS-USING CLARKE SPHEROID
      DIMENSION  B(70), AC(70)
      DATA (B(I),I=30,39)/1.847495,1.847781,1.848073,1.848372,
     C1.848673,1.848980,1.849290,1.849605,1.849922,1.850242/
     C(AC(I),I=30,39)/1.856937,1.857033,1.857132,1.857231,1.857331,
```

PRINTOUT OF ERROR GRID (Concluded)

```
C1.857435,1.857538,1.857643,1.857750,1.857858/
 DLAT=ALAT-YO
 DLONG=ALONG-XO
 IA=(YO+ALAT)/2.0
 AA=(AC(IA)+(AC(IA+1)-AC(IA))*((YO+ALAT)/2.0-IA))
 AA=AA*60.0*COS(0.01745329*ALAT)
 X=AA*DLONG
 BB=(B(IA)+(B(IA+1)-B(IA))*((YO+ALAT)/2.0-IA))*60.0
 Y=BB*DLAT
 RETURN
 END
```

PRINTOUT OF DO-ALL

```
C****PROGRAM DO-ALL---ITERATIVE-WEIGHTED-LEAST SQUARES EPICENTER LOCATION
C
C
      DIMENSION PHAS(30),LABEL(8),C(5),IPH(50),Q(50),SI(50),ID(50),
     2DC(50),S(50),A(50,4),W(4),DP(4),FDP(4)
      COMMON STAT(50),SLAT(50),SLONG(50)
C
C******READ STATIONS TO BE USED*********
  201 READ(5,109)ISTA,STAT(ISTA),SLAT(ISTA),SLONG(ISTA)
  109 FORMAT(I5,5X,A3,7X,2F10.4)
      IF (ISTA.EQ.50) GO TO 70
      WRITE(6,110) ISTA,STAT(ISTA),SLAT(ISTA),SLONG(ISTA)
  110 FORMAT(1X,I5,2X,A3,2F15.4)
      GO TO 201
   70 CONTINUE
C*****READ PARAMETERS FOR TRAVEL-TIME COMPUTATION***********
      CALL TTIME(PHAS)
C*****READ BASIC EQ DATA CARD CONTAINING ESTIMATES OF EPICENTER*******
C     THIS CARD SHOULD BE IN FORMAT OF CARD FILE OF EARTHQUAKES
  200 READ(5,100,END=99)IYR,MO,IDA,IHR,MIN,SEC,ELAT,ELONG,INT,BMAG,
     2IST,IQ,SP,(LABEL(JB),JB=1,8)
      IF (IYR.EQ.0) GO TO 99
  100 FORMAT(I4,4I2,F3.1,2F7.3,I2,F2.1,2I1,A4,8A5)
      WRITE(6,105)MO,IDA,IYR,IHR,MIN,SEC,ELAT,ELONG,(LABEL(JB),JB=1,8)
  105 FORMAT(2H1 ,I2,1H/,I2,1H/,I4/,4H  H=,I2,2X,I2,2X,F4.1/,6H  LAT=,
     2F7.3/,7H  LONG=,F7.3/,2X,A4,8A5//)
C*****READ WEIGHTS TO BE ASSIGNED IN COMPUTATION OF X,Y,T & Z
C     CAN ELIMINATE Z OR Z AND T BY SETTING TO ZERO EITHER WZ OR WZ & WT
      READ(5,101) WX,WY,WT,WZ,EZ,CDIST,NITER,SECERR,SMINER
  101 FORMAT(2X,6F8.3,I5,2F5.0)
      WRITE(6,101) WX,WY,WT,WZ,EZ,CDIST,NITER,SECERR
      IF(WZ.LT.0.0001)GO TO 22
      M=4
      GO TO 23
   22 IF(WT.LT.0.0001) GO TO 24
      M=3
      GO TO 23
   24 M=2
   23 TO=IHR*3600.+MIN*60.+SEC
      WRITE(6,120) IHR,MIN,SEC,TO,M
  120 FORMAT(1H ,2I5,2E20.6,I5)
      N=1
      W(1)=SQRT(WX)
      W(2)=SQRT(WY)
      W(3)=SQRT(WT)
      W(4)=SQRT(WZ)
C*****READ STATION,PHASE,ARRIVAL TIME DATA
      N=0
    6 N=N+1
      READ(5,102,END=5) IPH(N),ID(N),IH,IM,SEC,SI(N)
  102 FORMAT(I5,5X,I5,5X,2I3,F7.3,F10.3)
      Q(N)=IH*3600.0+IM*60.0+SEC
      IF (ID(N).LT.1) GO TO 5
      GO TO 6
```

PRINTOUT OF DO-ALL (Cont.)

```
    5 CONTINUE
      N=N-1
    7 CONTINUE
      WRITE(6,106)
  106 FORMAT(1H ,'STATION PHASE   HR MIN SEC        C1        C2        C3
     C  C4      C5      DIST     SEC   +OR-')
      DO 8 IN=1,N
      CALL ATIME (IPH(IN),TO,ID(IN),ELAT,ELONG,EZ,C,R)
      DC(IN)=Q(IN)-C(1)
      IID=ID(IN)
      IIPH=IPH(IN)
      IH=Q(IN)/3600.
      IM=(Q(IN)-IH*3600.)/60.
      SEC=Q(IN)-IH*3600.-IM*60.
      WRITE(6,107) STAT(IID),PHAS(IIPH),IH,IM,SEC,
     C(C(I),I=1,5),R,DC(IN),SI(IN)
  107 FORMAT(3X,A3,3X,A6,2X,I2,I4,F5.1,F10.1,4F7.3,F8.2,2F7.2)
      A(IN,1)=C(3)
      A(IN,2)=C(4)
      A(IN,3)=C(2)
      A(IN,4)=C(5)
      S(IN)=1.0/SQRT(SI(IN))
    8 CONTINUE
      CALL MAMAN(A,DC,S,W,N,DP,M)
      DO 14 I6=1,4
   14 FDP(I6)=DP(I6)*W(I6)
      TO=TO+FDP(3)
      ELAT=ELAT+FDP(2)/111.11
      ELONG=ELONG+FDP(1)/(111.11*COS(ELAT*0.01745))
      EZ=EZ+FDP(4)
      IHTO=TO/3600
      IMTO=(TO-IHTO*3600)/60
      TSEC=TO-IHTO*3600-IMTO*60
      WRITE(6,108) IHTO,IMTO,TSEC,ELAT,ELONG,EZ
  108 FORMAT(1H1,'THE RECOMPUTED EPICENTER IS'/2X,2I4,F7.2/2X,
     1'LATITUDE',F10.3/2X,'LONGITUDE',F10.3/2X,'DEPTH',3X,F7.1/2X)
      TESTC=SQRT(FDP(1)*FDP(1)+FDP(2)*FDP(2))
      IF (TESTC.LT.CDIST) GO TO 200
      IF(NITER.LT.0) GO TO 200
      NITER=NITER-1
      IF (SECERR.LT.SMINER) GO TO 7
      NRED=0
      DO 9 I=1,N
   92 DCS=ABS(DC(I+NRED)/S(I+NRED))
      IF (DCS.LT.SECERR) GO TO 9
      NRED=NRED+1
      JEND=N-NRED
      IF (JEND.LT.I) GO TO 91
      DO 10 J=I,JEND
      Q(J)=Q(J+1)
      ID(J)=ID(J+1)
      IPH(J)=IPH(J+1)
   10 SI(J)=SI(J+1)
      GO TO 92
    9 CONTINUE
      SECERR=SECERR/2.0
      N=N-NRED
```

PRINTOUT OF DO-ALL (Cont.)

```
      GO TO 7
   91 N=N-NRED+1
      IF (N.LE.M) GO TO 99
      GO TO 7
   99 STOP
      END
C
C
      SUBROUTINE TTIME(PHAS)
      DIMENSION C(5),A(20),B(20),DE(20),PHAS(30)
      COMMON STAT(50),SLAT(50),SLONG(50)
C*************************************************
C     DESIGNED FOR STRAIGHT LINE TRAVEL-TIME SEGMENTS
C     FOR WHICH A ZERO INTERCEPT AND SLOPE CAN BE DETERMINED
C     PRACTICAL DEPTH COMPUTATIONS RESTRICTED TO ONE LAYER CASE
C*************************************************
   49 READ(5,50) IPHA,A(IPHA),B(IPHA),DE(IPHA),PHAS(IPHA)
      IF(IPHA.EQ.20)RETURN
      WRITE(6,50)IPHA,A(IPHA),B(IPHA),DE(IPHA),PHAS(IPHA)
      GO TO 49
C*****BLANK CARD AT END*******
   50 FORMAT(I5,3F10.3,A6)
C*************************************************
C     INPUT FOR ENTRY ATIME IS DEFINED AS
C     IPH=PHASE IDENTITY,TO=ORIGIN TIME,ID=IDENTITY
C     OF STATION, (ELAT,ELNG)=ESTIMATED LOCATION (DEGREES)
C     EZ=DEPTH ESTIMATE, C=OUTPUT
      ENTRY ATIME(IPH,TO,ID,ELAT,ELONG,EZ,C,R)
      CALL CXY(SLAT(ID),SLONG(ID),ELAT,ELONG,X,Y)
      R=SQRT(X*X+Y*Y)
      C(1)=TO+A(IPH)*(2*DE(IPH)-EZ)+R*B(IPH)
      C(2)=1.0
      C(3)=X*B(IPH)/R
      C(4)=Y*B(IPH)/R
      C(5)=-A(IPH)
      RETURN
      END
C
C
      SUBROUTINE CXY(YO,XO,ALAT,ALONG,X,Y)
C*****(YO,XO) IS ORIGIN IN DEGREES<500KMFROM DATA FOR < .1KM ERROR
C*****(ALAT,ALONG) LATITUDE AND LONGITUDE OF DATA POINTS
C*****FROM RICHTER-ELEM SEIS-USING CLARKE SPHEROID
C*****LONGITUDE IS NEGATIVE FOR WEST, X IS POSITIVE EAST, Y IS POSITIVE
C     NORTH, (X,Y) IS DISTANCE TO (ALAT,ALONG) FROM ORIGIN (XO,YO)
      DIMENSION B(90),AC(90)
      DATA(B(I),I=20,45)/1.844998,1.845213,1.845437,1.845668,1.845907,
     C1.846153,1.846408,1.846670,1.846938,1.847213,1.847495,1.847781,
     C1.848073,1.848372,1.848673,1.848990,1.84929,1.849605,1.849922,
     C1.850242,1.850565,1.850890,1.851217,1.851543,1.851873,1.852202/
      DATA(AC(I),I=20,45)/1.856100,1.856173,1.856248,1.856325,1.856404,
     C1.856488,1.856573,1.856661,1.856750,1.856843,1.856937,1.857033,
     C1.857132,1.857231,1.857331,1.857435,1.857538,1.857643,1.857750,
     C1.857858,1.857964,1.858074,1.858194,1.858294,1.858403,1.858512/
      DLAT=ALAT-YO
      DLONG=ALONG-XO
      IA=(YO+ALAT)/2.0
```

PRINTOUT OF DO-ALL (Cont.)

```
      AA=(AC(IA)+(AC(IA+1)-AC(IA))*((YO+ALAT)/2.0-IA))
      AA=AA*60.0*COS(0.01745329*ALAT)
      X=AA*DLONG
      BB=(B(IA)+(B(IA+1)-B(IA))*((YO+ALAT)/2.0-IA))*60.0
      Y=BB*DLAT
      RETURN
      END
C
C
      SUBROUTINE MAMAN(A,DC,S,W,N,DP,M)
      DIMENSION A(50,4),DC(50),S(50),W(4),AN(50,4),ATA(4,4),AVRT(5,5),
     CATDC(4),DP(4)
      DO 7 I=1,N
      DC(I)=S(I)*DC(I)
      DO 7 J=1,M
    7 AN(I,J)=S(I)*A(I,J)*W(J)
      DO 20 IA=1,N
   20 WRITE(6,201)(AN(IA,JA),JA=1,M)
  201 FORMAT(1X,4F12.4)
      DO 8 L=1,4
      DO 8 LL=1,4
    8 ATA(L,LL)=0
      DO 9 I1=1,M
      DO 9 J1=1,M
      DO 9 K1=1,N
    9 ATA(I1,J1)=AN(K1,I1)*AN(K1,J1)+ATA(I1,J1)
      WRITE(6,202) ((ATA(IB,JB),IB=1,4),JB=1,4)
  202 FORMAT(1X//,(4(1X,F12.2)))
      M1=M+1
      CALL MINVRT(AVRT,ATA,M,M1)
      WRITE(6,203)((AVRT(IC,JC),IC=1,4),JC=1,4)
  203 FORMAT(2X//,(4(1X,F12.2)))
      DO 10 I2=1,4
   10 ATDC(I2)=0
      DO 11 I3=1,M
      DO 11 K3=1,N
   11 ATDC(I3)=AN(K3,I3)*DC(K3)+ATDC(I3)
      WRITE(6,204)(ATDC(IE),IE=1,4)
  204 FORMAT(2X//,(4(1X,F12.2)))
      DO 12 I4=1,4
   12 DP(I4)=0
      DO 13 I5=1,M
      DO 13 J5=1,M
   13 DP(I5)=AVRT(I5,J5)*ATDC(J5)+DP(I5)
      WRITE(6,205)(DP(IG),IG=1,4)
  205 FORMAT(2X//,(4(1X,F12.2)))
      RETURN
      END
C
C
      SUBROUTINE MINVRT(A,X,NN,MM)
      DIMENSION A(5,5),X(4,4)
C     MATRIX INVERSION SUBROUTINE,  A IS THE INPUT MATRIX,
C     X IS THE OUTPUT
    8 DO 9 I=1,NN
      DO 9 J=1,NN
    9 A(I,J)=X(I,J)
```

PRINTOUT OF DO-ALL (Concluded)

```
      DO 16 N=1,NN
      A(1,MM)=1.
      DO 10 I=2,MM
   10 A(I,MM)=0.
      DO 11 J=1,NN
   11 A(MM,J)=A(1,J+1)/A(1,1)
      DO 12 I=2,NN
      XX=A(I,1)
      DO 12 J=1,NN
   12 A(I-1,J)=A(I,J+1)-XX*A(MM,J)
      DO 16 J=1,NN
   16 A(NN,J)=A(MM,J)
      RETURN
      END
```

PRINTOUT OF SPECLE

```
C***************************************************************************
C*****SPECLE - PROGRAM FOR SPECTRAL ANALYSIS OF SEISMIC WAVES***********
C NDT (NO.OF INTERVALS),TTIME(LENGTH OF TIME) DT*NDT
C HEIGHT SCALE FACTOR MM/MM,LAB  2I5,4F10.3,4A6,I1
C DATA ( )H(I),T(I),I(1,N)  (10F7.1)
C HEIGHT SCALE FACTOR MM/MM,LAB  2I5,4F10.3,5A6
C DATA  0-193 MM TIME SCALE
      DIMENSION G(500),PH(500),T(1000),H(1000),F(2000),LAB(4),FN(2000)
      DIMENSION IBUFF(5000)
      CALL PLOTS(IBUFF(1),5000,41)
      PI2 =   6.2831853072
      NI=1
      NTOT=100
      IND=1
      READ(5,101,END=999) N,NDT,DT,TI,TCAL,HCAL,LAB,IV
  101 FORMAT (2I5,4F10.5,4A6,2X,I1)
      IF(N.EQ.0) GO TO 999
      WRITE (6,103) N,NDT,DT,TI,TCAL,HCAL,LAB,IV
  103 FORMAT(1H1,I5,44H  PAIRS OF POINTS ARE TO BE INTERPOLATED AT ,I5
     *,7H POINTS,F10.2,14H SECONDS APART,//13H BEGINNING AT, F10.3/
     *15H TCAL UNITS/SEC,1F10.3,15H HCAL UNITS/MM,1F10.3,//4A6,
     *5X,15HTYPE CORRECTION,I1)
      TTIME = DT*NDT
      NW = NDT / 2
      DF = 1.0 / TTIME
   47 READ(5,102)  (H(I),T(I),I=1,N)
  102 FORMAT(10F7.0)
      WRITE(6,104) (H(I),T(I),I=1,N)
  104 FORMAT(1X, 10F10.3)
      DO 20 I=1,N
   21 H(I)=H(I)*HCAL
   20 T(I)=T(I)/TCAL
      WRITE(6,180)
  180 FORMAT(1H1, 'VALUES OF H AND T CORRCECTED TO MM AND SEC'/)
      WRITE(6,105) (H(I),T(I),I=1,N)
  105 FORMAT(1X,10F10.3)
      CALL DIGI( H, T, N, TI, NDT, DT, F)
  600 CONTINUE
   48 DO 10 I=1,NDT
      F(I)=-F(I)
   10 FN(I)=I*DT
      CALL CALFT (FN,F,IBUFF,NDT,LAB)
      CALL STLNFT(FN,F,N,A,B,SGA,SGB)
  601 CONTINUE
      DO 11 I=1,NDT
   11 F(I)=F(I)-A*I*DT-B
      CALL SERTRA(0.0,NDT,NW,DF,G,PH,WO,F)
  221 CONTINUE
      GO TO (60,61,62), IV
   60 CONTINUE
      CALL WWSSC(NW,DF,G,PH)
       GO TO 602
   61 CONTINUE
      CALL SCSPC (NW,DF,G,PH)
```

PRINTOUT OF SPECLE (Cont.)

```
      GO TO 602
   62 CONTINUE
      CALL TIC (NW,DF,G,PH)
  602 CONTINUE
      WRITE(6,112) WO,DF,IV,(G(I),PH(I), I=1,NW)
  112 FORMAT(//17H DIRECT TRANSFORM,6H WO = ,2E17.7/10H   MODULUS,
     110H AND PHASE/,16H CORRECTION TYPE,I1,/1X,5(E15.6,F10.2))
      DO 12 J=1,NW
      FN(J)=LOG10(G(J))
      FN(J)=-FN(J)
   12 F(J)=LOG10(DF*FLOAT(J))
      CALL SPLOT(FN,F,IBUFF,NW,LAB)
  999 STOP
      END
C
C
      SUBROUTINE CALFT (FN,F,IBUFF,NDT,LAB)
      DIMENSION IBUFF(5000),FN(500),F(500),LAB(5)
      CALL PLOT(5.0,-10.0,-3)
      CALL PLOT(0.0,+3.0,-3)
      CALL SYMBOL (-1.5,0.0,0.14,LAB,90.,30)
      CALL SCALE (FN(1),5.0,NDT,+1)
      CALL SCALE (F(1),2.0,NDT,+1)
      CALL LINE(F(1),FN(1),NDT,+1,40,3)
      CALL AXIS(0.0,0.0,7HSECONDS,-7,5.0,90.,FN(NDT+1),FN(NDT+2))
      RETURN
      END
C
C
      SUBROUTINE STLNFT(X,Y,N,A,B,SGA,SGB)
      DIMENSION X(N), Y(N)
      SX =0.0
      SXX =0.0
      SY =0.0
      SYY =0.0
      SXY =0.0
      DO 325 I=1,N
      SX = SX + X(I)
      SXX = SXX + X(I)*X(I)
      SY = SY + Y(I)
      SYY =SYY +Y(I)*Y(I)
  325 SXY = SXY +X(I)*Y(I)
      AN = N
      DNOM = AN*SXX -SX*SX
      A = (AN*SXY -SX*SY)/DNOM
      B = (SY*SXX - SX*SXY)/DNOM
      D2 = SYY -A*SXY-B*SY
      SGA = SQRT (AN*D2/(DNOM*(AN-2.)))
      SGB = SQRT(SX*SX*D2/(DNOM*(AN-2.)))
      D2=SQRT(D2/AN)
      WRITE(6,326) A,SGA,B,SGB,D2
  326 FORMAT ( 30H LEAST SQUARE FIT, Y = A*X + B/3H A=,F13.6,4H+OR-,
     1E13.6,3H B=,E13.6,4H+OR-,E13.6,13HMIN DEVIATION,E15.6)
      RETURN
      END
C
C
```

PRINTOUT OF SPECLE (Cont.)

```
      SUBROUTINE TIC (NW,DF,G,PH)
C GT TAPE CORRECTION FROM AMP AND HALL-SEARS FREQ CURVES
      DIMENSION GTOR(23),FRET(23),G(NW),PH(NW)
      DATA FRET/.5,.75,1.0,1.25,1.5,1.75,2.0,2.5,3.0,4.0,5.0,
     *7.5,10.0,15.0,20.,30.,40.,50.,60.,70.,80.,90.,100./
      DATA GTOR/6.6,23.6,50.9,78.3,111.2,135.2,161.0,204.6,
     *253.,343.,435.,653.,871.,1306.,1689.,2454.,3061.,
     *3695.,4117.,4433.,4750.,5106.,5278./
      FMIN=0.50
      FMAX=100.0
      IF(DF.LT.0.50) GO TO 7
      FMIN=DF
    7 IF(NW*DF.GT.FMAX) GO TO 8
      FMAX=NW*DF
    8 ISTART=FMIN/DF +0.00001
      ISTOP=FMAX/DF
      J=1
      DO 18 I=ISTART,ISTOP
      FQ=I*DF
   40 IF(FQ.LT.FRET(J)) GO TO 42
      J=J+1
      GO TO 40
   42 VAL=GTOR(J-1)+(GTOR(J)-GTOR(J-1))*(FQ-FRET(J-1))/
     *(FRET(J)-FRET(J-1))
   18 G(I)=G(I)/VAL
      WRITE(6,1066) ISTART,ISTOP,DF
 1066 FORMAT(1H1,55HDATA CORRECTED FOR DISPLACEMENT RESPONSE BETWEEN IST
     *ART,I5,3H*DF,10HAND ISTOP ,I5,3H*DF,/6H DF = ,F8.3)
      RETURN
      END
C
C
      SUBROUTINE DIGI(H,T,N,TI,NDT,DT,F)
      DIMENSION H(I),T(I),F(NDT)
      PI=3.1415926536
      I=0
      DO 20 J=1,NDT
      TIME=TI + (J-1)*DT
   22 IF (T(I+1).GT.TIME) GO TO 20
      I=I+1
      GO TO 22
   20 F(J)=H(I)+(TIME-T(I))*(H(I+1)-H(I))/(T(I+1)-T(I))
      RETURN
      END
C
C
      SUBROUTINE SERTRA(DET,N,NW,DF,G,PH,WO,T)
C   DET = 0 TIME TO FREQ DOMAIN, NOT = 0 FREQ TO TIME, N=NUMBER OF TIME PO
C   NW=N/2 OR NO. OF FREQUENCY PTS. DF = FREQ INTERVAL = 1/T, T=N*DT
      DIMENSION G(NW),PH(NW),T(N),CFN(500),SFN(500)
      PI = 3.1415926536
      CF = 0.0174532925
      AN = N
      DO 119 I = 1,N
      A = I
      ARG = (6.28318531*A)/AN
      SFN(I) = SIN(ARG)
```

PRINTOUT OF SPECLE (Cont.)

```
119 CFN(I) = COS(ARG)
    IF (DET) 131,132,131
132 DO 133 I = 1,NW
     G(I) = 0.0
133 PH(I) = 0.0
     WO = 0.0
     DO 139 J = 1,NW
     X = 0.0
     Y = 0.0
     DO 140 I = 1,N
     IJ = I*J - N*((I*J-1)/N)
     X = X + T(I)*CFN(IJ)
140 Y = Y - T(I)*SFN(IJ)
    PH(J)=(ATAN2(-Y,-X))/CF +180.
139 G(J) = (1.0/(AN*DF*6.28318531))*SQRT(X*X + Y*Y)
     DO 134 I = 1,N
134 WO = WO +T(I)
     WO = (1.0/(AN*DF*6.28318531))*WO
    WRITE(6,112) WO,DF, (G(I),PH(I), I = 1,NW)
112 FORMAT(//17H DIRECT TRANSFORM,6H WO = ,2E17.7/10H   MODULUS,
   110H AND PHASE/ (1X,E15.6,F10.2,E15.6,F10.2,E15.6,F10.2,E15.6,F10.2
   2,E15.6,F10.2))
     RETURN
131 DO 142 I = 1,N
142  T(I) = WO/2.0
     DO 143  J = 1,NW
     NSG = (PH(J)/360.)*AN
     DO 143 I = 1,N
     IJ = I*J + NSG -N*((I*J + NSG - 1)/N)
143 T(I) =T(I) + G(J)*CFN(IJ)
     DO 144 I = 1,N
144 T(I) = 12.5663706*DF*T(I)
    DT = (1.0)/(AN*DF)
     RETURN
     END
C
C
      SUBROUTINE WWSSC(NW,DF,G,PH)
C   WORLD WIDE SEISMIC SYS. CORRECTION FROM FREQ RESPONSE CURVE
C   WWSSC (NW,G,DF,ISTART,ISTOP)
C   NW=NO. OF PTS. IN SPECTRA; G=MODULUS OF SPECTRA
C   DF=FREQ INCREMENT  1/T   T=TOTTAL TIME
      DIMENSION GCOR(11),FREQ(11),G(NW),PH(NW)
      DATA GCOR/.65,300.0,400.0,540.0,580.0,610.0,590.0,480.0,
     *310.0,38.0,1.8/
      DATA FREQ/.1,.8,1.0,1.25,1.43,1.67,2.00,2.50,
     *3.33,10.0,50.0/
      FMIN=0.1
      FMAX=50.0
      IF(DF.LT.0.1) GO TO 7
      FMIN=DF
    7 IF(NW*DF.GT.FMAX) GO TO 8
      FMAX=NW*DF
    8 ISTART=FMIN/DF+0.00001
      ISTOP=FMAX/DF
      J=1
      DO 18 I=ISTART,ISTOP
```

PRINTOUT OF SPECLE (Concluded)

```
      FQ=I*DF
   40 IF(FQ.LT.FREQ(J)) GO TO 42
      J=J+1
      GO TO 40
   42 VAL=GCOR(J-1)+(GCOR(J)-GCOR(J-1))*(FQ-FREQ(J-1))/
     *(FREQ(J)-FREQ(J-1))
   18 G(I)=G(I)/VAL
      WRITE(6,1066) ISTART,ISTOP,DF
 1066 FORMAT(1H1,55HDATA CORRECTED FOR DISPLACEMENT RESPONSE BETWEEN IST
     *ART,I5,3H*DF,10HAND ISTOP ,I5,3H*DF,/6H DF = ,F8.3)
      RETURN
      END
C
C
      SUBROUTINE SCSPC (NW,DF,G,PH)
C SGS,JKS CORRECTION, S.C.SEISMIC PROGRAM,FROM FREQ RESPONSE CURVE
      DIMENSION GSOR(18),FRES(18),G(NW),PH(NW)
      DATA FRES/.72,.8,.9,1.,1.2,2.0,3.,5.,7.,10.,12.2,20.,
     *30.,40.,50.,60.,70.,80./
      DATA GSOR/20.,22.,30.,38.,72.,120.,180.,310.,420.,580.,
     *880.,1010.,1050.,1075.,1080.,1067.,1060.,1020./
      FMIN=0.72
      FMAX=80.0
      IF(DF.LT.0.72) GO TO 7
      FMIN=DF
    7 IF(NW*DF.GT.FMAX) GO TO 8
      FMAX=NW*DF
    8 ISTART=FMIN/DF +0.00001
      ISTOP=FMAX/DF
      J=1
      DO 18 I=ISTART,ISTOP
      FQ=I*DF
   40 IF(FQ.LT.FRES(J)) GO TO 42
      J=J+1
      GO TO 40
   42 VAL=GSOR(J-1)+(GSOR(J)-GSOR(J-1))*(FQ-FRES(J-1))/
     *(FRES(J)-FRES(J-1))
   18 G(I)=G(I)/VAL
      WRITE(6,1066) ISTART,ISTOP,DF
 1066 FORMAT(1H1,55HDATA CORRECTED FOR DISPLACEMENT RESPONSE BETWEEN IST
     *ART,I5,3H*DF,10HAND ISTOP ,I5,3H*DF,/6H DF = ,F8.3)
      RETURN
      END
C
C
      SUBROUTINE SPLOT (FN,F,IBUFF,NW,LAB)
      DIMENSION IBUFF(5000),FN(500),F(500),LAB(5)
      CALL PLOT(5.0,-10.0,-3)
      CALL PLOT(0.0,+3.0,-3)
      CALL SYMBOL (-1.0,0.0,0.14,LAB,90.,30)
      FN(NW+1)=0.0
      FN(NW+2)=1.0
      F(NW+1)=-1.0
      F(NW+2)= 0.5
      CALL LINE (FN,F,NW,+1,40,3)
      CALL LGAXIS (0.0,+0.0,2HHZ, +3,6.0,90., 0.1,0.5)
      CALL AXIS (5.0,-1.0,12HLOG DIS SPEC,+12,5.0,180.,-3.0,1.0)
      RETURN
      END
```

APPENDIX B

GRAVITY DATA COLLECTION AND ANALYSIS

Gravity data were compiled from existing surveys made near the Clark Hill Reservoir area and from measurements taken on twenty field surveys (GT 90--GT 109). For convenience these surveys were tied into local base stations established in the Clark Hill area. A listing of these base stations and their respective gravity values appears in Table 9, as well as an estimated precision for each base.

Three gravity meters were employed during the course of the surveys and in order to insure uniformity in data acquisition all measurements between bases were made by a single operator on the same instrument. Data were reduced by standard linear interpolation to remove effects due to instrumental drift. All surveys were closed within six hours to minimize instrumental drift and compensate for tidal effects. Drift was computed for each survey leg and it appears, with the corresponding instrument, in Table 10. Latitude corrections were applied and Bouguer anomalies computed for all points using a standard correction density of 2.67 gm/cm^3 to allow comparison with existing maps. Combined drift and instrumental reading errors are considered to be on the order of $\pm$ 0.3 milligal. Errors due to elevation on land stations amount to $\pm$ 0.15 milligal. Combined error in the total reduction process is considered to be less than $\pm$ 0.45 milligal. This figure has been substantiated by comparing the values obtained from

Table 9. List of Base Stations Used for Gravity Surveys

Station Name	Station Coordinates		Gravity Value	Precision (Milligals)
	Latitude	Longitude		
McCormick, S.C.	33°55.12'	82°12.95'	979635.117	± 0.03
Savannah R.	33°51.30'	82°23.50'	979632.648	± 0.05
Soap Creek	33°50.03'	82°25.73'	979632.414	± 0.05
Fish Beach	33°51.59'	82°25.22'	979636.664	± 0.05
Elijah Clark	33°51.25'	82°24.16'	979631.875	± 0.05
Homer Legg	33°41.59'	82°20.42'	979616.727	± 0.07
Missletoe	33°38.86'	82°22.20'	979609.141	± 0.07

Table 10. Instrumental Drift for Gravity Surveys

GT Survey No.	Gravity Meter	Station Nos.	Drift (Mgal per Hr)
91	North American AGl No. 68	1-17	-0.040
91	North American AGl No. 68	17-29	-0.026
92	Worden No. 316 Model 113	1-17	0.265
92	Worden No. 316 Model 113	17-23	0.120
94	Worden No. 316 Model 113	1-24	0.000
95	Worden No. 316 Model 113	1-6	0.058
95	Worden No. 316 Model 113	6-9	0.000
95	Worden No. 316 Model 113	10-15	0.061
95	Worden No. 316 Model 113	15-29	0.019
95	Worden No. 316 Model 113	29-31	-0.166
96	LaCoste-Romberg No. G65	1-16	-0.010
96	LaCoste-Romberg No. G65	16-24	0.011
97	Worden No. 316 Model 113	1-16	0.056
97	Worden No. 316 Model 113	16-19	0.000
98	LaCoste-Romberg No. G65	1-18	0.008
98	LaCoste-Romberg No. G65	19-24	0.012
99	LaCoste-Romberg No. G65	1-5	-0.017
100	Worden No. 316 Model 113	1-6	0.125
101	LaCoste-Romberg No. G65	1-12	-0.014
101	LaCoste-Romberg No. G65	12-32	0.011
102	LaCoste-Romberg No. G65	1-17	-0.006
103	Worden No. 316 Model 113	1-27	0.032
103	Worden No. 316 Model 113	27-38	0.369
104	LaCoste-Romberg No. G65	1-5	0.025
105	Worden No. 316 Model 113	1-18	0.091
106	LaCoste-Romberg No. G65	1-17	0.001
106	LaCoste-Romberg No. G65	17-41	0.001
107	Worden No. 316 Model 113	1-10	0.025
107	Worden No. 316 Model 113	11-20	0.261
108	North American AGl No. 68	1-8	0.062
109	North American AGl No. 68	1-6	-0.054
109	North American AGl No. 68	6-24	-0.032

the reoccupation of several stations by different survey personnel with different instruments. Using the North American Gravity Meter AGl No. 68, surveys GT 108-109 reoccupied several stations for which all computed Bouguer anomalies were found to be within 0.28 milligal.

All data used in compiling the map were coded in the standard Department of Defense format and are listed in this Appendix. Reoccupied stations and bases were removed and the data were plotted and contoured manually.

The technique of Talwani, Worzel, and Landisman (1959) was used to compute theoretical gravity profiles for two dimensional models along lines AA' and BB'.

PRINTOUT OF 2DPROF

```
C GRAVITY PROFILING FOR 2-DIMENSIONAL STRUCTURES
C GRAVITY FOR 2-DIMENSIONAL STRUCTURES(AFTER-TALWANI,WORTZEL,LANDISMAN)
C   INPUT(2I10,3F10.3)   CARD NO. ONE
C       LL=NO. OF POLYGONS, NDX=NO. OF GRAVITY VALUES, DX=SEPARATION OF
C       GRAVITY VALUES, XO=POSITION OF FIRST GRAVITY VALUE, SCALE=PLOT
C       SCALE-FOR DRAW
C IF SCALE=0. PROGRAM CALCULATES SCALE
C IF SCALE=13. NO GRAPH IS DRAWN
C   INPUT(FREE FIELD)  LL CARDS
C       NXZ=NO.+1OF CORNERS OF POLYGON TAKEN CLOCKWISE, DRHO=DENSITY
C       CONTRAST, X(I,J),Z(I,J)=CORDINATES OF CORNERS-JTH CORNER OF ITH
C       POLYGON
C   REPEAT SEQUENCE FOR ADDITIONAL PROFILES
C   BLANK CARD AT END TO TERMINATE CALCULATION
      DIMENSION DRHO(50),X(50,20),Z(50,20),NN(50),XX(20),ZZ(20),GAL(500)
   25 READ (5,500) LL,NDX,DX,XO   , SCALE
      WRITE(6,503) LL,NDX,DX,XO
  503 FORMAT(1H1,28HVERTICAL GRAVITY ANOMALY FOR,I5, 9H POLYGONS/2X,
     13HTHE,I5,16H-GRAVITY VALUES,,F10.4,19H-KM.APART, BEGIN AT,F10.4)
      IF(LL)  26,26,27
   27 DO 100 I=1,LL
  500 FORMAT (2I10,3F10.5)
      READ(5,501)  NXZ,DRHO(I),(X(I,J),Z(I,J),J=1,NXZ)
      WRITE(6,502)  NXZ,DRHO(I), (X(I,J),Z(I,J),J=1,NXZ)
  501 FORMAT( )
  502 FORMAT(16H NO OF POINTS = ,I10,22H DENSITY DIFFERENCE = /(1X,10F10
     <.3/))
  100 NN(I) = NXZ
      DO 101 I=1,LL
      NNI = NN(I)
      DO 101  J = 1,NNI
  101 X(I,J) = X(I,J) -XO
      DO 102I=1,NDX
      G=0.0
      DO 103 J=1,LL
      NNJ = NN(J)
      DO 104 K = 1,NNJ
      XX(K) =X(J,K)
  104 ZZ(K)=Z(J,K)
      CALL TWLZ(NN(J),XX,ZZ,DRHO(J),GA)
  103 G= G+GA
      GAL(I) = G
      DO 110 M=1,LL
      NNM = NN(M)
      DO 110 N = 1, NNM
  110 X(M,N) = X(M,N)-DX
  102 CONTINUE
      WRITE(6,505) (GAL(I),I=1,NDX)
  505 FORMAT(1X//24H GRAVITY ANOMALY IN MGAL,/(5F15.8))
      ISC=SCALE
      IF(ISC.EQ.13) GO TO 25
      IF(SCALE) 130,131,130
  131 CALL MXSCL(NDX,GAL,SCALE)
  130 CALL DRAW(NDX,1,GAL,SCALE)
```

PRINTOUT OF 2DPROF (Cont.)

```
      GO TO 25
   26 STOP
      END
C
C
      SUBROUTINE TWLZ(K1,XX,ZZ,DRHO,GA)
C  USES METHOD OF TALWANI, WORZEL, AND LANDISMAN (JGR 1959 PP 49-59)
C  TO GIVE GRAVITY ANOMALY AT X=0,Z=0. IN MGAL FOR TWO DIMENSIONED
C BODY IN VERTICAL PLANE DESCRIBED BY A POLYGON (IN KILOMETERS
      DIMENSION XX(K1),ZZ(K1)
      PI = 3.141592654
      KK = K1-1
      GA = 0.0
      DO 100 K=1,KK
      K2 = K+1
      IF(XX(K)*ZZ(K2)-XX(K2)*ZZ(K))  30,100,30
   30 IF(XX(K)-XX(K2)) 85,20,85
   20 XZ =        ((XX(K2)**2 + ZZ(K2)**2)/(XX(K)**2 + ZZ(K)**2))
      DG = 0.5*LOG(XZ)*XX(K)
      GO TO 99
   85 IF(ZZ(K)-ZZ(K2))  235,72,235
   72 DG = ZZ(K)*(ATAN2(ZZ(K2),XX(K2))-ATAN2(ZZ(K),XX(K)))
      GO TO 99
  235 A =(XX(K2)-XX(K))/(ZZ(K2)-ZZ(K))
      B = (XX(K)*ZZ(K2) - XX(K2)*ZZ(K))/(ZZ(K2)-ZZ(K))
      IF(XX(K))  200,201,200
  201 DG = (B/(1.+A*A))*(.5*LOG((XX(K2)*XX(K2)+ZZ(K2)*ZZ(K2))/(ZZ(K)*
     1  ZZ(K))) - A*(ATAN2(ZZ(K2),XX(K2))-PI/2.))
  200 IF(XX(K2))  31,210,31
  210 DG = (B/(1.+A*A))*(.5*LOG(ZZ(K2)*ZZ(K2)/(XX(K)*XX(K)+
     1  ZZ(K)*ZZ(K))) + A*(ATAN2(ZZ(K),XX(K)) - PI/2.))
   31 DG=LOG((XX(K2)*XX(K2)+ZZ(K2)*ZZ(K2))/(XX(K)*XX(K)+ZZ(K)*ZZ(K)))
      DG=(B/(1.0+A*A))*(0.5*DG-A*(ATAN2(ZZ(K2),XX(K2))-ATAN2(ZZ(K),
     1XX(K))))
   99 GA=(13.34)    *DRHO*DG + GA
  100 CONTINUE
      RETURN
      END
C
C
      SUBROUTINE MXSCL(N,A,AMAX)
      DIMENSION A(N)
      AMAX = 0
      DO 26 I = 1,N
      IF (ABS(A(I))-AMAX) 26,26,25
   25 AMAX = ABS(A(I))
   26 CONTINUE
      RETURN
      END
C
C
      SUBROUTINE DRAW (NTOT, INC, F, SCALE)
C   NTOT=TOTAL NUMBER OF POINTS IN F.  F IS THE DATA (ONE DIMENSIONAL)
C   TO BE PLOTTED. INC IS THE SAMPLE INTERVAL FOR PLOTTING F.
C   SCALE IS THE AMPLITUDE OF ONE FULL SCALE DEFLECTION
      DIMENSION    F(NTOT)
      DATA AA1/1H /,AA2/1H*/,AA3/1H+
```

PRINTOUT OF 2DPROF (Concluded)

```
      WRITE(6,1011) SCALE,(I,I=-9,10)    , (AA2,M=1,21)
 1011 FORMAT(1H1,E14.8,17H-MGALS FULL SCALE/3X,20I5/2X,22A5)
 10   DO 1501 K = 1, NTOT, INC
      FK = 50.*F(K)/SCALE
      KI = FK/50
      KK = FK - KI*50.+50.5
      WRITE (6,511) AA2, (AA1,I=1,KK),AA2
  511 FORMAT (1X,110A1)
 1501 CONTINUE
      RETURN
      END
```

LISTING OF GRAVITY DATA

```
C*****LISTING OF GRAVITY DATA FOR THE CLARK HILL RESERVOIR**************
C*****GEORGIA TECH SURVEYS 90 - 107, 20 - 22, WOOLARD DATA
C
C
      335169 - 822522 1       991         3635664  1740    635  GT90 GA 1
      335125 - 822416 1      1128         3631875  1744    486  GT91 GA 1
      335069 - 822408 1      1329         3627914  2047    565  GT91 GA 1
      335060 - 822492 1      1326         3627922  2051    572  GT91 GA 1
      334915 - 822684 1      1350         3626133  2148    642  GT91 GA 1
      334843 - 822758 1      1478         3622883  2318    669  GT91 GA 1
      334820 - 822836 1      1454         3622664  2254    632  GT91 GA 1
      335018 - 822844 1      1157         3630977  1924    622  GT91 GA 1
      335070 - 822918 1      1481         3623703  2094    442  GT91 GA 1
      335181 - 823056 1      1311         3625609  1605    143  GT91 GA 1
      335335 - 823153 1      1487         3621586  1256-   403  GT91 GA 1
      335271 - 823313 1      1518         3619313  1490-   203  GT91 GA 1
      335451 - 823610 1      1436         3612461   300-  1302  GT91 GA 1
      335514 - 823771 1      1423         3610234-   48-  1636  GT91 GA 1
      335731 - 823734 1      1341         3619180   289-  1207  GT91 GA 1
      335101 - 822715 1      1402         3627109  2146    582  GT91 GA 1
      335004 - 822460 1      1207         3629814  1951    604  GT 9 GA 1
      334835 - 822380 1      1375         3623953  2117    584  GT91 GA 1
      334890 - 822207 1      1183         3629969  2050    730  GT91 GA 1
      334639 - 822250 1      1417         3617664  1891    310  GT91 GA 1
      334511 - 822006 1      1286         3616270  1525     91  GT 9 GA 1
      334411 - 821861 1      1323         3619635  2113    637  GT 9 GA 1
      334507 - 821960 1      1274         3618212  1688    267  GT 9 GA 1
      334511 - 822086 1      1439         3616791  2048    443  GT 9 GA 1
      334342 - 822211 1      1258         3617398  1818    403  GT91 GA 1
      334510 - 822352 1      1341         3614633  1533     37  GT91 GA 1
      334349 - 822471 1      1463         3618750  2127    495  GT91 GA 1
      335069 - 822408 1      1128         3631875  1822    564  GT91 GA 1
      335174 - 822579 1       991         3636453  1711    606  GT92 GA 1
      335220 - 822623 1       991         3637023  1705    600  GT92 GA 1
      335253 - 822666 1       991         3637680  1724    619  GT92 GA 1
      335282 - 822730 1       991         3637555  1671    566  GT92 GA 1
      335290 - 822813 1       991         3636406  1544    439  GT92 GA 1
      335346 - 822843 1       991         3636570  1484    379  GT92 GA 1
      335397 - 822892 1       991         3636734  1427    322  GT92 GA 1
      335437 - 822942 1       991         3636586  1359    254  GT92 GA 1
      335502 - 823011 1       991         3634977  1107      2  GT92 GA 1
      335565 - 823059 1       991         3635070  1029-    76  GT92 GA 1
      335622 - 823170 1       991         3634508   892-   213  GT92 GA 1
      335553 - 823198 1       991         3632070   745-   360  GT92 GA 1
      335487 - 823203 1       991         3631367   768-   337  GT92 GA 1
      335473 - 823332 1       991         3627414   391-   714  GT92 GA 1
      335642 - 823464 1       991         3637273   863-   242  GT92 GA 1
      335717 - 823418 1       991         3635008   811-   294  GT92 GA 1
      335668 - 823350 1       991         3631734   552-   553  GT92 GA 1
      335642 - 823287 1       991         3631094   525-   580  GT92 GA 1
      335645 - 823220 1       991         3633930   802-   303  GT92 GA 1
      335143 - 822387 1       991         3635523  1661    556  GT94 GA 1
      335092 - 822285 1       991         3635063  1686    581  GT94 GA 1
      335052 - 822247 1       991         3634523  1686    581  GT94 GA 1
```

LISTING OF GRAVITY DATA (Cont.)

055	335019	-	822203	1	991	3633594	1639	534	GT94	GA	1
056	335001	-	822261	1	991	3633906	1695	590	GT94	GA	1
057	334951	-	822379	1	991	3633289	1703	598	GT94	GA	1
058	334993	-	822336	1	991	3634055	1723	618	GT94	GA	1
059	334931	-	822490	1	991	3633438	1746	641	GT94	GA	1
060	334903	-	822511	1	991	3633594	1801	696	GT94	GA	1
061	334989	-	822517	1	991	3634828	1805	700	GT94	GA	1
062	335020	-	822604	1	991	3634984	1778	673	GT94	GA	1
063	335007	-	822697	1	991	3634602	1758	653	GT94	GA	1
064	335020	-	822733	1	991	3635141	1793	688	GT94	GA	1
065	335020	-	822796	1	991	3634750	1755	650	GT94	GA	1
066	335033	-	822664	1	991	3634984	1759	654	GT94	GA	1
067	335003	-	822128	1	991	3632898	1592	487	GT94	GA	1
068	334983	-	822079	1	991	3636063	1937	832	GT94	GA	1
069	334950	-	822043	1	991	3638148	2191	1086	GT94	GA	1
070	334919	-	822013	1	991	3636297	2049	944	GT94	GA	1
071	334879	-	821986	1	991	3634445	1919	814	GT94	GA	1
072	334868	-	822084	1	991	3635297	2021	916	GT94	GA	1
073	335309	-	822915	1	991	3633313	1209	104	GT95	GA	1
074	335273	-	822918	1	991	3635922	1521	416	GT95	GA	1
075	335251	-	822970	1	991	3634750	1433	328	GT95	GA	1
076	335512	-	821295	1	1372	3635117	2283	753	GT95	GA	1
077	335003	-	822573	1	1055	3632414	1742	566	GT95	GA	1
078	335130	-	822350	1	1064	3632656	1619	432	GT95	GA	1
079	335101	-	822380	1	1326	3628039	2004	525	GT95	GA	1
080	335050	-	822758	1	1021	3633523	1683	544	GT95	GA	1
081	334987	-	822833	1	991	3633313	1657	552	GT95	GA	1
082	335175	-	822708	1	1335	3628407	1967	478	GT 9	GA	1
083	335181	-	822798	1	1411	3626138	1967	393	GT 9	GA	1
084	335096	-	822879	1	1448	3624859	2070	455	GT 9	GA	1
085	335061	-	823070	1	1472	3622398	1947	305	GT95	GA	1
086	335119	-	823075	1	1430	3624172	1914	319	GT95	GA	1
087	335094	-	823218	1	1600	3620648	2123	338	GT95	GA	1
088	335168	-	823179	1	1417	3623719	1762	181	GT95	GA	1
089	335205	-	823288	1	1369	3622875	1476-	50	GT95	GA	1
090	335348	-	823217	1	1417	3621180	1257-	324	GT95	GA	1
091	335523	-	823072	1	1356	3625359	1345-	168	GT95	GA	1
092	335526	-	823075	1	1439	3624977	1317-	288	GT95	GA	1
093	335605	-	823201	1	1280	3629609	1320-	108	GT95	GA	1
094	335003	-	822573	1	1055	3632414	1742	566	GT95	GA	1
095	335130	-	822350	1	1064	3632648	1617	430	GT95	GA	1
096	335091	-	822612	1	1338	3629258	2178	686	GT95	GA	1
097	335385	-	823098	1	1393	3625422	1555	1	GT96	GA	1
098	335379	-	822928	1	1158	3632516	1548	256	GT96	GA	1
099	335254	-	823119	1	1250	3626891	1443	49	GT96	GA	1
100	335348	-	823218	1	1417	3620859	1225-	356	GT96	GA	1
101	335436	-	823578	1	1439	3613688	383-	1222	GT96	GA	1
102	335551	-	823569	1	1250	3618086	149-	1245	GT96	GA	1
103	335535	-	823487	1	1469	3615367	577-	1062	GT96	GA	1
104	335579	-	823393	1	1335	3620656	632-	857	GT96	GA	1
105	335513	-	823386	1	1381	3620500	708-	832	GT96	GA	1
106	335516	-	823415	1	1228	3623867	571-	799	GT96	GA	1
107	335591	-	823275	1	1372	3621781	838-	692	GT96	GA	1
108	335539	-	823364	1	1234	3622477	558-	819	GT96	GA	1
109	335515	-	823698	1	1021	3617906-	525-	1664	GT96	GA	1
110	335789	-	823671	1	1298	3622031	363-	1085	GT96	GA	1
111	335781	-	823623	1	1280	3624102	524-	904	GT96	GA	1

LISTING OF GRAVITY DATA (Cont.)

112	335768	-	823572	1	1204	3626508	549-	794	GT96	GA	1
113	335739	-	823488	1	1234	3627867	819-	558	GT96	GA	1
114	335690	-	823770	1	1049	3621281-	345-	1514	GT96	GA	1
115	335617	-	823721	1	1387	3613063-	22-	1569	GT96	GA	1
116	335549	-	823627	1	1231	3618398-	12-	1386	GT95	GA	1
117	335125	-	822356	1	991	3633633	1498	393	GT97	GA	1
118	334850	-	821958	1	991	3630453	1561	456	GT97	GA	1
119	334792	-	821940	1	991	3628516	1448	343	GT97	GA	1
120	334822	-	821877	1	991	3628430	1398	293	GT97	GA	1
121	334765	-	821837	1	991	3626625	1267	162	GT97	GA	1
122	334754	-	821839	1	991	3625992	1247	142	GT97	GA	1
123	334710	-	821845	1	991	3625438	1253	148	GT97	GA	1
124	334659	-	821887	1	991	3624961	1277	172	GT97	GA	1
125	334635	-	821950	1	991	3624258	1240	135	GT97	GA	1
126	334599	-	821863	1	991	3625789	1442	337	GT97	GA	1
127	334637	-	821821	1	991	3626469	1459	354	GT97	GA	1
128	334660	-	821754	1	991	3627156	1495	390	GT97	GA	1
129	334591	-	821689	1	991	3628445	1719	614	GT97	GA	1
130	335429	-	823403	1	991	3627016	413-	692	GT97	GA	1
131	335384	-	823487	1	991	3627703	543-	562	GT97	GA	1
132	334927	-	822605	1	1320	3626531	2078	606	GT98	GA	1
133	334785	-	822683	1	1113	3628547	1836	595	GT98	GA	1
134	334729	-	822646	1	1058	3627992	1783	569	GT98	GA	1
135	334715	-	822645	1	1247	3624320	1925	535	GT98	GA	1
136	334763	-	822543	1	1286	3624805	2028	593	GT98	GA	1
137	334718	-	822427	1	1372	3623359	2209	679	GT98	GA	1
138	334884	-	822428	1	1359	3624500	2084	558	GT98	GA	1
139	334913	-	822265	1	1295	3627266	2096	651	GT98	GA	1
140	334929	-	822166	1	1231	3629047	2053	680	GT98	GA	1
141	334911	-	822360	1	1317	3625555	1993	524	GT98	GA	1
142	334838	-	822448	1	1317	3624453	1984	515	GT98	GA	1
143	334762	-	822446	1	1219	3628148	2158	798	GT98	GA	1
144	334906	-	822424	1	1036	3632250	1720	564	GT98	GA	1
145	335030	-	822399	1	1311	3627789	2032	570	GT98	GA	1
146	335044	-	822381	1	1271	3628711	1982	564	GT98	GA	1
147	335028	-	822306	1	1173	3630344	1866	557	GT98	GA	1
148	335348	-	823474	1	1036	3626922	656-	500	GT98	GA	1
149	335801	-	823448	1	1204	3633797	1231-	112	GT98	GA	1
150	335833	-	823480	1	1173	3636273	1341	32	GT98	GA	1
151	335850	-	823519	1	1173	3637938	1484	175	GT98	GA	1
152	335965	-	823620	1	1347	3637281	1765	262	GT98	GA	1
153	334159	-	822042	1	1049	3616727	1326	157	GT99	GA	1
154	333886	-	822220	1	997	3609141	785-	327	GT99	GA	1
155	333954	-	822228	1	1000	3611398	927-	189	GT 0	GA	1
156	334028	-	822207	1	1000	3614750	1159	44	GT 0	GA	1
157	334060	-	822118	1	1000	3614773	1118	3	GT 0	GA	1
158	334166	-	821836	1	1000	3616102	1104-	11	GT 0	GA	1
159	334391	-	822170	1	1241	3617469	1670	287	GT 1	GA	1
160	334429	-	822121	1	997	3622047	1323	211	GT 1	GA	1
161	334478	-	822089	1	1213	3616891	1407	54	GT 1	GA	1
162	334433	-	822040	1	1155	3620461	1648	360	GT 1	GA	1
163	334465	-	822212	1	1021	3622727	1416	277	GT 1	GA	1
164	334462	-	821818	1	1219	3620102	1769	409	GT 1	GA	1
165	334480	-	821765	1	1408	3619781	2297	726	GT 1	GA	1
166	334504	-	821668	1	1445	3620078	2406	795	GT 1	GA	1
167	334563	-	821636	1	1234	3623502	2017	640	GT 9	GA	1
168	334541	-	822297	1	1128	3618930	1261	3	GT 1	GA	1

LISTING OF GRAVITY DATA (Cont.)

169	334591	-	822259	1	1387	3616336	1731	184	GT	1	GA	1
170	334531	-	822209	1	1250	3617211	1479	85	GT	1	GA	1
171	334513	-	822170	1	1067	3619805	1198	8	GT	1	GA	1
172	334548	-	821902	1	1234	3620844	1772	395	GT	1	GA	1
173	334556	-	821851	1	1167	3621930	1662	360	GT	1	GA	1
174	334589	-	821828	1	1143	3623445	1693	418	GT	1	GA	1
175	334577	-	822201	1	1417	3618945	1967	386	GT	1	GA	1
175	334718	-	822160	1	1393	3620906	2030	476	GT	1	GA	1
177	334727	-	822088	1	1320	3620859	1788	315	GT	1	GA	1
178	334759	-	822047	1	1298	3622547	1845	397	GT	1	GA	1
179	334774	-	822100	1	1113	3630188	2015	774	GT	1	GA	1
180	334824	-	822157	1	1155	3632391	2299	1011	GT	1	GA	1
181	334730	-	822012	1	1234	3620633	1498	121	GT	1	GA	1
182	334818	-	821995	1	1158	3627109	1788	496	GT	1	GA	1
183	334647	-	822347	1	1426	3618383	1981	390	GT	1	GA	1
184	334741	-	822411	1	1158	3627914	1975	683	GT	1	GA	1
185	334782	-	822319	1	1067	3630547	1898	708	GT	1	GA	1
185	334747	-	822287	1	1366	3623516	2166	643	GT	1	GA	1
187	334444	-	822396	1	1341	3613281	1489-	7	GT	2	GA	1
188	334405	-	822424	1	1158	3616969	1346	54	GT	2	GA	1
189	334333	-	822471	1	1244	3616016	1614	227	GT	2	GA	1
190	334299	-	822515	1	1097	3619641	1573	349	GT	2	GA	1
191	334280	-	822617	1	1207	3616508	1625	279	GT	9	GA	1
192	334219	-	822663	1	1280	3615597	1844	416	GT	9	GA	1
193	334180	-	822610	1	1292	3614313	1808	366	GT	2	GA	1
194	334146	-	822483	1	1292	3614418	1865	424	GT	9	GA	1
195	334178	-	822751	1	1204	3616427	1749	406	GT	9	GA	1
196	334142	-	822793	1	1033	3621250	1753	600	GT	2	GA	1
197	334051	-	822858	1	1372	3613852	2185	655	GT	2	GA	1
198	334051	-	822944	1	1393	3613789	2245	692	GT	2	GA	1
199	334036	-	822814	1	1326	3613758	2054	575	GT	2	GA	1
200	334017	-	822750	1	1280	3614703	2034	606	GT	2	GA	1
201	333984	-	822669	1	1137	3617328	1901	632	GT	2	GA	1
202	333793	-	822366	1	1366	3599563	1094-	429	GT	3	GA	1
203	333635	-	822384	1	1530	3594000	1266-	441	GT	3	GA	1
204	333540	-	822279	1	1494	3592375	984-	682	GT	3	GA	1
205	333670	-	822142	1	1472	3591750	813-	829	GT	3	GA	1
206	333772	-	822221	1	1417	3599000	1227-	354	GT	3	GA	1
207	333657	-	822071	1	1490	3591586	871-	792	GT	3	GA	1
208	333663	-	821966	1	1490	3591266	830-	833	GT	3	GA	1
209	333669	-	821894	1	1369	3594281	748-	778	GT	3	GA	1
210	333707	-	821773	1	1292	3595047	537-	905	GT	3	GA	1
211	333721	-	821664	1	1362	3595508	779-	741	GT	3	GA	1
212	333766	-	821736	1	1323	3596273	672-	804	GT	3	GA	1
213	333848	-	821863	1	1000	3604914	424-	691	GT	3	GA	1
214	333885	-	821922	1	1289	3603808	1165-	273	GT	3	GA	1
215	333942	-	822022	1	1521	3599188	1331-	366	GT	3	GA	1
216	334035	-	822053	1	1136	3606664	914-	408	GT	3	GA	1
217	334000	-	821889	1	1423	3601641	1194-	394	GT	3	GA	1
218	334040	-	821913	1	1305	3602414	850-	605	GT	3	GA	1
219	333877	-	821526	1	1329	3597844	694-	788	GT	3	GA	1
220	333961	-	821567	1	1131	3603859	567-	694	GT	3	GA	1
221	333633	-	821688	1	1189	3603000	1114-	212	GT	3	GA	1
222	333759	-	822035	1	1472	3594961	1011-	631	GT	3	GA	1
223	333868	-	822030	1	1463	3599125	1248-	384	GT	3	GA	1
224	333709	-	822068	1	1481	3593102	922-	730	GT	3	GA	1
225	333699	-	822401	1	1487	3597344	1378-	281	GT	3	GA	1

LISTING OF GRAVITY DATA (Cont.)

225	333861 - 822319 1	1408	3601344	1310-	260	GT 3 GA 1
227	333890 - 822310 1	1518	3602922	1766	73	GT 3 GA 1
228	333916 - 822294 1	1332	3603953	1260-	226	GT 3 GA 1
229	333873 - 822344 1	1335	3604266	1360-	129	GT 3 GA 1
230	333949 - 822313 1	1045	3613391	1273	107	GT 3 GA 1
231	333839 - 822454 1	1250	3605148	1233-	161	GT 3 GA 1
232	333804 - 822526 1	1210	3605719	1215-	134	GT 3 GA 1
233	333878 - 822480 1	1146	3607820	1125-	153	GT 3 GA 1
234	333908 - 822531 1	1009	3613484	1227	102	GT 3 GA 1
235	333870 - 822271 1	1268	3603930	1124-	291	GT 3 GA 1
236	334402 - 822522 1	1402	3612930	1700	136	GT 4 GA 1
237	334455 - 822540 1	1402	3615781	1911	347	GT 4 GA 1
238	334537 - 822622 1	1436	3618180	2140	539	GT 4 GA 1
239	334058 - 822310 1	1003	3617570	1409	290	GT 5 GA 1
240	333980 - 822382 1	1003	3614766	1237	118	GT 5 GA 1
241	333949 - 822463 1	1003	3614586	1262	143	GT 5 GA 1
242	334023 - 822471 1	1003	3618195	1520	401	GT 5 GA 1
243	334066 - 822414 1	1003	3621734	1815	696	GT 5 GA 1
244	334106 - 822327 1	1003	3621703	1756	638	GT 5 GA 1
245	334094 - 822254 1	1003	3617984	1399	281	GT 5 GA 1
246	334132 - 822180 1	1003	3617273	1276	157	GT 5 GA 1
247	334153 - 822253 1	1003	3622953	1815	696	GT 5 GA 1
248	334188 - 822349 1	1003	3623930	1865	746	GT 5 GA 1
249	334224 - 822444 1	1003	3622594	1681	563	GT 5 GA 1
250	334236 - 822346 1	1003	3623180	1723	604	GT 5 GA 1
251	334292 - 822358 1	1003	3622375	1566	447	GT 5 GA 1
252	334208 - 822276 1	1003	3623117	1756	637	GT 5 GA 1
253	334211 - 822182 1	1003	3624719	1911	792	GT 5 GA 1
254	334221 - 822067 1	1003	3623695	1795	677	GT 5 GA 1
255	334599 - 822728 1	1234	3623859	2002	625	GT 6 GA 1
256	334651 - 822770 1	1189	3624891	1893	567	GT 6 GA 1
257	334731 - 822823 1	1478	3620711	2256	607	GT 6 GA 1
258	334679 - 822513 1	1417	3621695	2239	658	GT 6 GA 1
259	334629 - 822562 1	1265	3623789	2047	636	GT 6 GA 1
260	334579 - 822549 1	1506	3617117	2193	514	GT 6 GA 1
261	334544 - 822459 1	1433	3615852	1890	292	GT 6 GA 1
262	334528 - 822389 1	1402	3615781	1812	248	GT 6 GA 1
263	334435 - 822481 1	1387	3612626	1577	30	GT 9 GA 1
264	334370 - 822642 1	1402	3615773	2029	465	GT 6 GA 1
265	334446 - 822695 1	1500	3616977	2344	671	GT 6 GA 1
266	334536 - 822754 1	1535	3616590	2436	668	GT 6 GA 1
267	334608 - 822810 1	1463	3618875	2197	565	GT 6 GA 1
268	334672 - 822825 1	1231	3624469	1952	578	GT 6 GA 1
269	334702 - 822860 1	1533	3619727	2368	658	GT 6 GA 1
270	334537 - 822860 1	1548	3617844	2456	728	GT 6 GA 1
271	334472 - 822843 1	1533	3617258	2439	729	GT 6 GA 1
272	334429 - 822783 1	1469	3617258	2302	664	GT 6 GA 1
273	334368 - 822753 1	1311	3617867	1959	497	GT 6 GA 1
274	334325 - 822829 1	1469	3615172	2238	600	GT 6 GA 1
275	334310 - 822778 1	1402	3615727	2207	643	GT 6 GA 1
276	334314 - 822695 1	1402	3615430	2074	510	GT 6 GA 1
277	334234 - 822543 1	1018	3619785	1433	297	GT 9 GA 1
278	334178 - 822508 1	1234	3616345	1834	457	GT 9 GA 1
279	334243 - 822719 1	1301	3615427	1860	408	GT 9 GA 1
280	334251 - 822779 1	1372	3613272	1849	319	GT 9 GA 1
281	334266 - 822839 1	1456	3613633	2156	521	GT 6 GA 1
282	334228 - 822857 1	1356	3614586	1966	453	GT 6 GA 1

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283	334179	-	822830	1	1230	3617563	2096	668	GT 6 GA 1
284	333945	-	822720	1	1038	3615570	1628	414	GT 6 GA 1
285	333913	-	822767	1	1035	3615734	1681	470	GT 6 GA 1
286	334101	-	822905	1	1280	3617430	2191	763	GT 6 GA 1
287	334148	-	822907	1	1036	3619727	1604	448	GT 6 GA 1
288	334207	-	822913	1	1352	3614857	2043	523	GT 6 GA 1
289	334298	-	822882	1	1437	3614398	2253	594	GT 6 GA 1
290	334393	-	822854	1	1512	3616789	2437	751	GT 6 GA 1
291	334302	-	822434	1	1250	3616203	1696	302	GT 6 GA 1
292	334264	-	822402	1	1146	3619352	1744	466	GT 6 GA 1
293	334221	-	822067	1	1000	3623438	1759	644	GT 7 GA 1
294	333904	-	821718	1	1000	3605695	427-	689	GT 7 GA 1
295	333947	-	821298	1	1000	3605234	320-	796	GT 7 GA 1
296	333877	-	821288	1	1085	3602078	365-	845	GT 7 GA 1
297	333929	-	821395	1	1000	3605234	345-	771	GT 7 GA 1
298	333956	-	821417	1	1204	3600906	505-	838	GT 7 GA 1
299	334036	-	821339	1	1000	3607414	415-	700	GT 7 GA 1
300	333983	-	821446	1	1000	3605492	295-	820	GT 7 GA 1
301	333585	-	822456	1	1463	3594477	1175-	457	GT 7 GA 1
302	333826	-	822865	1	1000	3614031	1366	251	GT 7 GA 1
303	333778	-	822851	1	1122	3608070	1214-	37	GT 7 GA 1
304	333806	-	822827	1	1000	3610820	1073-	43	GT 7 GA 1
305	333872	-	822857	1	1055	3614039	1474	298	GT 7 GA 1
306	334051	-	822945	1	1393	3613852	2251	697	GT 7 GA 1
307	334114	-	822010	1	1000	3616266	1191	75	GT 7 GA 1
308	333981	-	821710	1	1000	3609133	662-	453	GT 7 GA 1
309	334080	-	821592	1	1000	3611281	740-	375	GT 7 GA 1
310	334361	-	821734	1	1006	3625503	1792	670	GT 9 GA 1
311	334361	-	821635	1	1119	3624452	2035	787	GT 9 GA 1
312	335905	-	823254	1	1538	3634711	2270	532	GT20 SC 9
313	335325	-	822803	1	1471	3631234	1764	124	GT20 SC 9
314	335588	-	822776	1	1558	3626734	2006	235	GT20 SC 9
315	335427	-	822475	1	1414	3633063	2328	751	GT20 SC 9
316	335750	-	822345	1	1143	3638578	1593	318	GT20 SC 9
317	335380	-	82 453	1	1673	3628055	1995	129	GT20 SC 9
318	335757	-	82 761	1	1341	3626289	965-	531	GT20 SC 9
319	335806	-	821200	1	1551	3641016	3018	1288	GT20 SC 9
320	335927	-	821561	1	1603	3642805	3189	1401	GT20 SC 9
321	335937	-	821938	1	1600	3638273	2712	927	GT21 SC 9
322	335678	-	821788	1	1649	3630875	2483	644	GT21 SC 9
323	335512	-	821295	1	1372	3635117	2283	753	GT21 SC 9
324	335542	-	82 956	1	1411	3617969	648-	926	GT21 SC 9
325	335546	-	82 327	1	1408	3620516	888-	683	GT21 SC 9
326	335565	-	82 50	1	1475	3630945	2111	465	GT21 SC 9
327	335240	-	82 138	1	1100	3630914	1403	176	GT21 SC 9
328	334990	-	82 190	1	1414	3623180	1946	368	GT21 SC 9
329	334952	-	82 604	1	1106	3627180	1450	215	GT21 SC 9
330	335097	-	82 906	1	1271	3621711	1208-	210	GT21 SC 9
331	335149	-	821262	1	1335	3624258	1589	99	GT21 SC 9
332	335197	-	821846	1	1344	3631125	2237	738	GT21 SC 9
333	334915	-	821771	1	1177	3627273	1727	414	GT21 SC 9
334	334807	-	821393	1	1247	3627289	2094	703	GT21 SC 9
335	334783	-	821060	1	1003	3631086	1755	636	GT21 SC 9
336	334744	-	82 802	1	1128	3624750	1561	303	GT21 SC 9
337	334597	-	82 586	1	1459	3610563	1400-	239	GT21 SC 9
338	334704	-	82 307	1	1408	3619727	1896	325	GT21 SC 9
339	335205	-	82 546	1	1134	3624250	890-	375	GT21 SC 9

LISTING OF GRAVITY DATA (Cont.)

340	333779	- 82 52	1		1000	3605344		563	-	552	GT22	SC	1
341	333950	- 82 317	1		1015	3607438		541	-	591	GT22	SC	1
342	334139	- 82 456	1		1151	3605859		614	-	681	GT22	SC	1
343	334387	- 82 212	1		1393	3606008		1001	-	553	GT22	SC	1
344	334304	- 82 584	1		1353	3606953		1005	-	504	GT22	SC	1
345	334362	- 82 983	1		1247	3607680		751	-	640	GT22	SC	1
346	334158	- 82 755	1		930	3607320		158	-	879	GT22	SC	1
347	333512	- 82 108	1		896	3602422		322	-	678	GT22	SC	1
348	+333050	-0821220	1	+	1110	359370	+	75	-	49	0	2094	1650
349	+333050	-0824850	1	+	1958	359550	+	354	+	135	0	2094	1650
350	+333070	-0820260	1	+	1027	359280	+	37	-	77	1	3584	6880
351	+333100	-0820480	1	+	1122	359190	+	53	-	71	0	2094	1650
352	+333210	-0823960	1	+	1679	359330	+	224	+	36	0	2094	1650
353	+333280	-0821890	1	+	911	360040	+	48	-	53	0	2094	1650
354	+333290	-0823060	1	+	1611	358930	+	152	-	27	0	2094	1650
355	+333330	-0825380	1	+	1882	359000	+	237	+	26	0	2094	1650
356	+333340	-0823490	1	+	1710	359430	+	226	+	34	0	2094	1650
357	+333370	-0824770	1	+	1852	359200	+	242	+	35	0	2094	1650
358	+333410	-0821120	1	+	652	360540	+	10	-	62	0	2094	1650
359	+333440	-0825830	1	+	1891	358730	+	198	-	13	0	2094	1650
360	+333530	-0823340	1	+	1058	360780	+	143	+	21	1	3582	6880
361	+333620	-0822380	1	+	1527	359330	+	120	-	50	0	2094	1650
362	+333660	-0821950	1	+	1476	359160	+	82	-	82	0	2094	1650
363	+333680	-0823400	1	+	1453	360310	+	187	+	24	0	2094	1650
364	+333680	-0825250	1	+	1596	359750	+	175	-	2	0	2094	1650
365	+333730	-0821440	1	+	1018	360250	+	40	-	73	0	2094	1650
366	+333750	-0824000	1	+	1500	360800	+	241	+	73	0	2094	1650
367	+333760	-0822850	1	+	1116	360810	+	122	-	2	0	2094	1650
368	+333830	-0821000	1	+	1012	359990	-	1	-	114	1	3584	6880
369	+333860	-0824660	1	+	1248	361620	+	230	+	90	0	2094	1650
370	+333910	-0825850	1	+	1430	361180	+	235	+	75	0	2094	1650
371	+333970	-0822010	1	+	1324	360290	+	105	-	42	0	2094	1650
372	+334050	-0823740	1	+	1547	360560	+	190	+	17	0	2094	1650
373	+334050	-0825170	1	+	1748	359980	+	194	-	1	0	2094	1650
374	+334290	-0822890	1	+	1467	361400	+	222	+	56	0	2094	1650
375	+334370	-0825920	1	+	1971	360150	+	235	+	15	0	2094	1650
376	+334410	-0821840	1	+	972	362580	+	165	+	56	0	2094	1650
377	+334420	-0825370	1	+	1957	359760	+	185	-	33	0	2094	1650
378	+334430	-0824450	1	+	1866	360210	+	207	-	3	0	2094	1650
379	+334440	-0821230	1	+	1231	361590	+	142	+	4	1	2052	1865
380	+334450	-0821320	1	+	1051	363280	+	257	+	138	1	3584	6880
381	+334530	-0820300	1	+	1533	360250	+	88	-	82	1	2052	1865
382	+334540	-0822390	1	+	1418	361580	+	184	+	26	0	2094	1650
383	+334600	-0823610	1	+	1710	361350	+	243	+	52	0	2094	1650
384	+334700	-0824950	1	+	2010	359860	+	173	-	51	0	2094	1650
385	+334730	-0822890	1	+	1431	362210	+	225	+	65	0	2094	1650
386	+334800	-0825500	1	+	1778	359440	+	45	-	153	0	2094	1650
387	+334850	-0824150	1	+	1651	360970	+	142	-	42	0	2094	1650
388	+335030	-0823070	1	+	1471	362310	+	205	+	41	0	2094	1650
389	+335050	-0822510	1	+	1323	362810	+	207	+	59	0	2094	1650
390	+335170	-0824460	1	+	1954	360050	+	109	-	108	0	2094	1650
391	+335210	-0823930	1	+	1720	360060	+	32	-	159	0	2094	1650
392	+335230	-0825180	1	+	1801	360160	+	65	-	136	0	2094	1650
393	+335370	-0825940	1	+	1765	360960	+	114	-	83	0	2094	1650
394	+335480	-0821800	1	+	1531	362750	+	224	+	46	1	2052	1865
395	+335530	-0820680	1	+	1591	360570	-	1	-	178	1	2052	1865
396	+335570	-0823400	1	+	1317	362040	+	56	-	91	0	2094	1650

LISTING OF GRAVITY DATA (Concluded)

397	+335530	-0824140	1	+	1424	361930	+	69	-	89	0	2094	1650
398	+335740	-0825630	1	+	1946	361140	+	137	-	80	0	2094	1650
399	+335620	-0824580	1	+	1213	365070	+	292	+	157	1	3582	6880
400	+335[illegible]50	-0822800	1	+	1478	363090	+	172	+	7	1	2052	1865
401	+335930	-0824530	1	+	1195	365440	+	308	+	174	0	2094	1650
402	+335960	-0823870	1	+	1425	363490	+	180	+	20	0	2094	1650
403	33470	- 82359	1		377	338960		19	-	23		1	

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